TECHNICAL REPORT
NATICK/TR-06/011

AD__________________

DEVELOPMENT OF NON-STANDARD WEARABLE CONNECTORS FOR A USB 2.0 TEXTILE CABLE

by

T. Wilson
and
J. Slade

Foster-Miller, Inc.
Waltham, MA 02451-1196

March 2006

Final Report
November 2001 – January 2003

Approved for public release; distribution is unlimited

Prepared for
U.S. Army Research, Development and Engineering Command
Natick Soldier Center
Natick, Massachusetts 01760-5019

REPORT DOCUMENTATION PAGE						*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
	Final	14 Nov 2001–17 Jan 2003

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
DEVELOPMENT OF NON-STANDARD WEARABLE CONNECTORS FOR A USB 2.0 TEXTILE CABLE	DAAD16-02-P-0042
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Wilson, T. Slade, J.	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Foster-Miller, Inc. 350 Second Avenue Waltham, MA 02451-1196	NLB-020100-1741
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSORING/MONITOR'S ACRONYM(S)**
U.S. Army Research, Development and Engineering Command Natick Soldier Center Kansas Street Natick, MA 01760-5011	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A soldier-based Personal Area Network (PAN) that can be unobtrusively integrated into the soldier ensemble is desirable for soldier comfort, weight savings, and the expanded mission capabilities that come with netted communication and improved situational awareness. In this Phase I effort a series of innovative concepts were investigated for connectors that interface with an electrotextile-based PAN. These concepts included connection methods common to the textiles industry to achieve electrical connectivity. These included snapping, sliding and buckling mechanisms. Particular attention was paid to the buckle style connector and its potential for rapid integration into the Scorpion Bravo system.

15. SUBJECT TERMS

ELECTRICAL CONNECTORS	ARMY PERSONNEL	FABRICS	CLOTHING
USB(UNIVERSAL SERIAL BUS)	EMBEDDING	SENSES(PHYSIOLOGY)	CONNECTORS
ELECTRIC CABLES	TEXTILES	SCORPION PROGRAM	WEAR
DISMOUNTED SOLDIERS	WEAVING	HUMAN FACTORS ENGINEERING	

16. SECURITY CLASSIFICATION OF:			17. LIMITATATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Carole Winterhalter
U	U	U	SAR	50	19b. TELEPHONE NUMBER *(Include area code)* 508-233-5460

CONTENTS

Section **Page**

LIST OF FIGURES AND TABLES

Figure **Page**

FIGURES (Continued)

Figure **Page**

TABLE

PREFACE

A soldier-based Personal Area Network (PAN) that can unobtrusively be integrated into the soldier ensemble is desirable for soldier comfort, weight savings, and expanded mission capabilities that come with netted communication and improved situational awareness. Cables with round profiles such as those traditionally used with computers pose snag hazards, are uncomfortable, and lack the environmental ruggedness for soldier applications. Narrow fabric electrotextile cables have been developed for the soldier, but electrical/mechanical connectors that are compatible with the narrow fabric form factor are needed.

During the period from November 2001 through January 2003, Foster-Miller, Inc., Waltham, MA investigated a series of innovative concepts for connectors that interface with an electrotextile-based PAN. These concepts included connection methods common to the textiles industry to achieve electrical connectivity, including snapping, sliding, and buckling mechanisms. Particular attention was paid to the buckle style connector and its potential for rapid integration into the Scorpion Bravo system. This report provides technical details of that project which was funded under Natick Contract DAAD16-02-P-0042.

The citation of trade names in this report does not imply endorsement or any other approval of said products by the Government.

DEVELOPMENT OF NON-STANDARD WEARABLE CONNECTORS FOR A USB 2.0 TEXTILE CABLE

1. EXECUTIVE SUMMARY

1.1 Program Objectives

The original objective of this program was to design and produce prototypes of three connector schemes that would allow data and power to be transmitted across the dismounted soldier's uniform. This program was to culminate in the delivery of a written report, design diagrams, and first level prototypes of the three different connection schemes integrated with narrow woven Universal Serial Bus (USB) cables. Two of the connector concepts were designed to connect the device securely to the body in easy-to-use sliding and snapping motions. The third connector was a modification of a Military Specification (MIL-SPEC) buckle that would allow discontinuous interfaces to be bridged on the soldier's uniform. Because of the high cost of manufacturing molds for three connector systems, each consisting of a male and female half, the design effort was divided into two phases. This first phase, described here, was intended to allow these three designs to be prototyped before embarking on mold fabrication in the optional Phase II portion.

Approximately two-thirds of the way through the Phase I design process, the decision was made by all parties to alter the scope of the work to bring it in line with the Scorpion Bravo system. This alteration of the Statement of Work called for one of the three initially proposed designs to be downselected for rapid insertion into the Scorpion Bravo system. At this point in the program, a buckle style connector was felt to be the most viable and useful of the three options. All further work on the other connector concepts was halted at this point.

A key aspect of Foster-Miller's approach to meeting both the original and modified objectives was to assure that the connector and its integration into the network was designed from the outset using fightability and wearability principles. This was to assure that the soldier's ability to fight and perform normal operational tasks was not degraded in any way, as compared to currently fielded systems (Legacy) or soon to be fielded systems (Land Warrior).

To accomplish these goals, the program was divided into the following five tasks [Note: These tasks apply to both the original program and the modified Statement of Work (SOW)]:

- Task 1 – Connector Requirements Modification.
- Task 2 – Generate Design Drawings.
- Task 3 – Rapid Prototyping of Design Concepts.
- Task 4 – Ergonomic Evaluation and Refinement of Connector Design.
- Task 5 – Reporting and Status Meetings.

1.2 Conclusions

The principal conclusions that were drawn from this Phase I effort to design innovative connector concepts were:

Buckle Connector

- The proposed hybrid connector concept is composed of a buckle connector where the center guide pin is replaced with a commercial off-the-shelf (COTS) electrical connector. Due to the difficulties of providing a high degree of protection from the ingress of foreign particles and moisture, it is suggested that environmental sealing is best accomplished using a COTS electrical connector with a guaranteed protection index, rather than modifying the buckle connector to serve the same purpose.

- Overmolding the connector's release sleeve will immobilize it and may result in an undesirably high pullout force.

- The latching mechanism on most COTS connectors cannot be removed without compromising the connector's environmental seal. However, the latch retention pullout force can be tailored by altering the latching pins.

- While various connector styles can be successfully incorporated into a buckle connector, environmentally sealed connectors may be undesirable for some applications as they require a relatively bulky buckle design relative to their pin count. Consequently, the buckle concept will likely be most suitable for commercial applications where a high degree of environmental protection is not required.

- Due to concerns over bulk, Foster-Miller does not recommend the integration of an environmentally sealed buckle style connector into the Scorpion Bravo system.

- Non-environmentally sealed buckle connectors can be made quite small and may be desirable for consumer products such as wearable computing platforms.

Other Connector Concepts

- Dovetail connectors, and in fact any connector designs that require a sliding action, are extremely difficult to environmentally seal. One advantage of this type of design, however, is that contaminants are easy to remove from electrical contacts due to the wiping inherent in the sliding action.

- Electrical connections made with a latching motion similar to that found in cell phone batteries are simple to implement and are relatively easy to environmentally seal.

- Snap connectors are relatively simple to implement and can be used to transmit both power and data. They are not, however, suited to the rigors of outdoor military use as the female side tends to clog up with dirt and mud when not connected.

1.3 Brief Background

Today's complex geo-political climate has forced the U.S. Armed Services into new operational strategies. The prevalence of international terrorism, the threat from chemical and biological weapons, and the "three-block" operational mission has placed increasing demands on the military. An outgrowth of these pressures has been the development of concepts such as the 'battle force,' the 'vertical battlefield,' and the 'digitized soldier.' Each of these concepts relies on rapidly redeployable troops which have enhanced decision-making capability brought about through rapid transfer and dissemination of information to each member of the squad. Tactical Internet (TI) provides the means to distribute this information to the soldier on the battlefield. What is missing is the ability to process and use this information via an intranet at the level of the individual soldier for the benefit of the squad. For example, if a chemical weapon sensor were intranetted to the radio, it could relay a signal to other squad members to don protective clothing, thereby enhancing unit survivability.

Systems and devices that gather information (e.g., laser target identifier, Global Positioning System (GPS), Chemical & Biological Weapons (CBW) sensors, Combat Identification (ID), etc.) are either part of the current soldier system or are under development. However, a network to link these devices on the body and to facilitate inter-communication of this key information without hindering military operations is lacking. This program focused on the development of the needed networking technology.

A more specific objective of this effort was to develop and deliver prototypes of our innovative connector concepts. During the course of the program, this objective was modified to focus on the development of a single connector design and its integration into the Scorpion soldier ensemble. The Scorpion soldier system is currently in the Phase II portion of its development and is a joint effort between the U.S. Army, Crye Associates, Exponent, Foster-Miller, and Artisent. In addition to the connector work done on this program, Foster-Miller is also engaged in two other efforts, DAAD16-02-C-0006 and DAAD16-02-C-0046, to design data cables and connectors for this system. The Scorpion system contains an electrical network in the form of attached narrow woven buses which will assist soldiers in completing their assigned mission. A key aspect of Foster-Miller's approach to meeting the program objectives was to assure that the network was designed from the outset using fightability and wearability principles, i.e., to assure that the uniform neither degrades the soldier's ability to fight nor to perform normal operational tasks while wearing it. This effort was essential in order to assure military acceptance.

Information on fightability and wearability was obtained from a number of sources. Foremost among these sources are the Arthur D. Little study on fightability (1) performed for the Natick Soldier Center (NSC) and the Carnegie-Mellon University (CMU) study on wearability (2) performed for the Defense Advanced Research Projects Agency (DARPA). The information from these studies was combined with results from related Foster-Miller efforts to provide the technology base for the design, fabrication and testing of a novel electro-textile based connector system.

Several key user needs and system requirements needed to be addressed during the development of these connector concepts and their integration into the Scorpion system. These included:

1. Data and power transmission across non-connected interfaces (e.g., from pants to coat, sleeve to glove, undershirt to jacket), or discontinuous interfaces (i.e., across the center placket of a Battle Dress Uniform (BDU) jacket). One of the key requirements for this functionality is that it not restrict the soldier's mobility or prevent rapid doffing of the system.

2. Connecting external devices to the PAN network. Here, two different classes of devices may have to be integrated: 1) devices not connected to the body or uniform (battery packs, computer module, radio, etc.), and 2) other devices that connect to the uniform (e.g., small sensors, fabric-based antenna, etc.). These connections require fresh hybrid design rules specifying how to transition from textile to device while operating in a military environment.

3. Regardless of the connection type, the connector system must be lightweight, ergonomic, and take up minimal volume within the system. Due to the aggressive performance required in the new operational directive a premium must be placed on solutions that allow the soldier to be both swift and agile.

4. All connector solutions must be designed to withstand mechanical abuse, and environmental contaminants such as dust, saltwater and mold. Connectors should also be capable of attaching securely to cable shielding so as to minimize the soldier's EMI signature.

Specific objectives for this program are listed below. These objectives reflect both the original program goals and the SOW changes that took effect 6 months into the program:

- Investigate a wide range of novel means for connecting electronics devices to the soldier PAN and transmitting data and power across non-connected interfaces within the soldier ensemble. This phase focused on ease of use of the connect/disconnect mechanism, ability to waterproof, user comfort, etc.

- Downselect several connector designs and generate a series of Comptuer-Aided Design (CAD) drawings for further evaluation. [Note: The most promising of these designs were to be used to generate prototypes in the original SOW.]

- Select connector components for chosen designs. If necessary, modify or make recommendations for modifying them to assure they are sufficiently robust for the military environment.

- Perform a laboratory evaluation of the potential to transfer power and data across non-interconnected interfaces in the uniform. [This objective was de-emphasized when the SOW was modified.]

- Integrate most applicable connector design into the Scorpion Bravo system for further evaluation.

2. PROGRAM TASKS

As discussed in the prior section, connector concepts that facilitate the integration of an electrotextile PAN into the soldier ensemble are desirable for soldier comfort, weight savings, and the expanded mission capabilities that come with netted communication and improved situational awareness. At the beginning of this program, three connector types were identified as having excellent potential for this application: snap, dovetail and buckle connectors.

During the Phase I program, the objectives of the research effort were to answer the following questions [Note: These objectives apply to both the original program and the modified SOW]:

- What are the best locations on the body for incorporating these connector concepts from the standpoint of ergonomics and electrical functionality?

- What are most ergonomic form factors?

- How will the proposed connector concepts be protected from environmental effects such as dust and moisture?

- How will these connectors interface with an electrotextile network?

To accomplish these goals, the program was divided into the following five tasks [Note: These tasks apply to both the original program and the modified SOW]:

- Task 1 – Connector Requirements Modification.
- Task 2 – Generate Design Drawings.
- Task 3 – Rapid Prototyping of Design Concepts.
- Task 4 – Ergonomic Evaluation and Refinement of Connector Design.
- Task 5 – Reporting and Status Meetings.

Specific accomplishments made within each of these task areas are discussed in detail in Section 3.

3. TASK-BY-TASK DESCRIPTION OF ACCOMPLISHMENTS

3.1 Task 1 - Connector Requirements Modification

Early in the program, a meeting was held between Foster-Miller and Plastics One to assess the feasibility of the three general connectorization concepts presented in the Phase I proposal. One important consideration that was identified in this discussion, and in discussions with BAE Systems on Contract No. DAAB07-02-C-P201, was the electromagnetic interaction between the various subsystems comprising the soldier ensemble. The presence of an electronic network and placement of electronic "boxes" or modules within that network affects antenna systems on the body, and therefore antenna requirements must be considered in the design of connector systems. Any "metal box" which is overlaid on an antenna will affect its performance by acting as an electrical shield. In addition, any separate electrical network will act as an antenna in the presence of a working antenna and may cause interference. These realities directly influence the form and placement of electrical connectors and cables, particularly with regard to EMI shielding, as placement of electronics modules over the antenna radiator can compromise performance. Therefore, our initial designs, which assumed that the electronics modules would be placed on the outside of the garment system, were found to need modification in terms of placement and grounding requirements. Serious consideration was therefore given to concepts which allowed the integration of the network and antenna system in such a way that antenna-to-module and module-to-module interference was minimized.

We now believe that electronics modules need to be located in a layer of the garment closer to the body in order to avoid interference with the antenna suite. User access to these connectors is therefore slightly different than what we had originally envisioned. In addition, the integration of the electronics network and body-borne antenna forces the electronics to take a more body-conscious shape. Body-conscious shapes have interior contours that are body conformal, thicknesses that stay within the body's aura or personal space, exterior contours that do no inhibit motion and activity, and limits on areas and placement of hard, nonelastic components. The best set of body shapes for devices is shown in Figure 1. Figure 1 illustrates the idea of a modularized system of electronics packages distributed across the body so as to minimize their perceived impact on the user. This particular distribution of forms came out of a study performed at the Institute for Complex Engineering Systems (ICES) at CMU. Both Foster-Miller and Plastics One agreed to use these pod-like forms for housing electronics modules attached to the narrow woven network system. Foster-Miller contacted CMU and requested access to the pods.

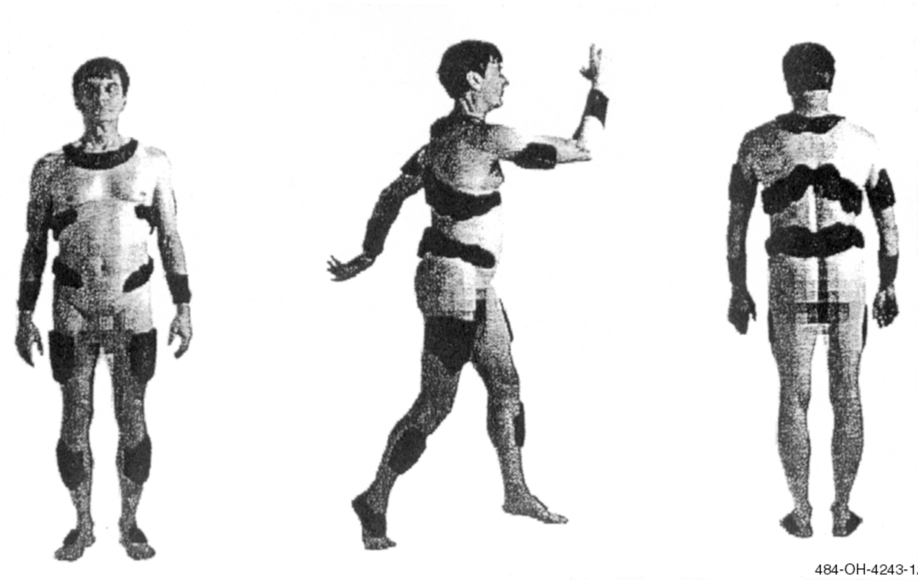


Figure 1. Modular forms shown attached to the human body

3.2 Task 2 – Generate Design Drawings and Task 3 – Rapid Prototyping of Design Concepts

3.2.1 MIL-SPEC Buckle Connector

Figure 2 shows Foster-Miller's original concept for a modified military spec plastic buckle which would allow power and data to be transmitted across non-connected interfaces on a vest or jacket. Advantages of this concept are:

- It is a familiar and well accepted physical form.
- Its ability to accept the current USB connector spec part.
- Its secure mechanical lock which imparts stability to the connection.

Two military buckles were selected for further consideration (Figure 3). The SR-1 Fastex connector shown on the bottom is the connector currently used on the MOLLE vests. According

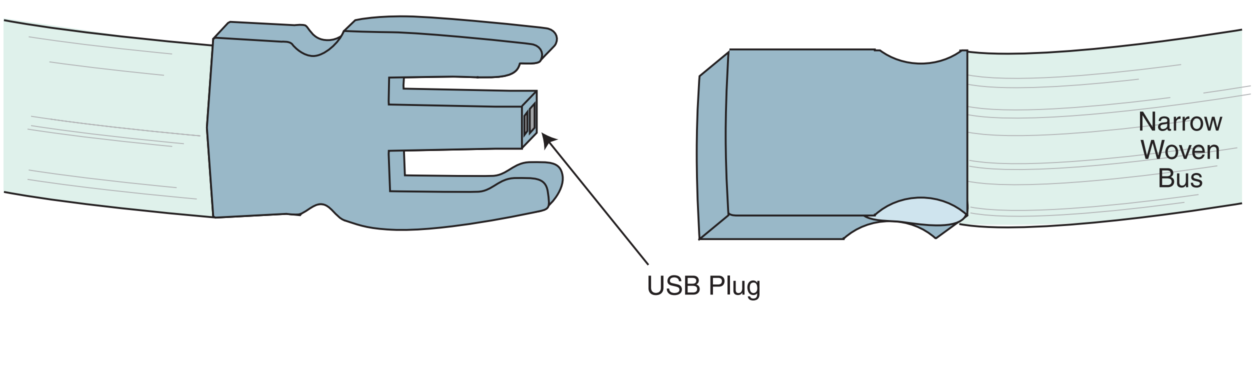


Figure 2. Initial buckle concept

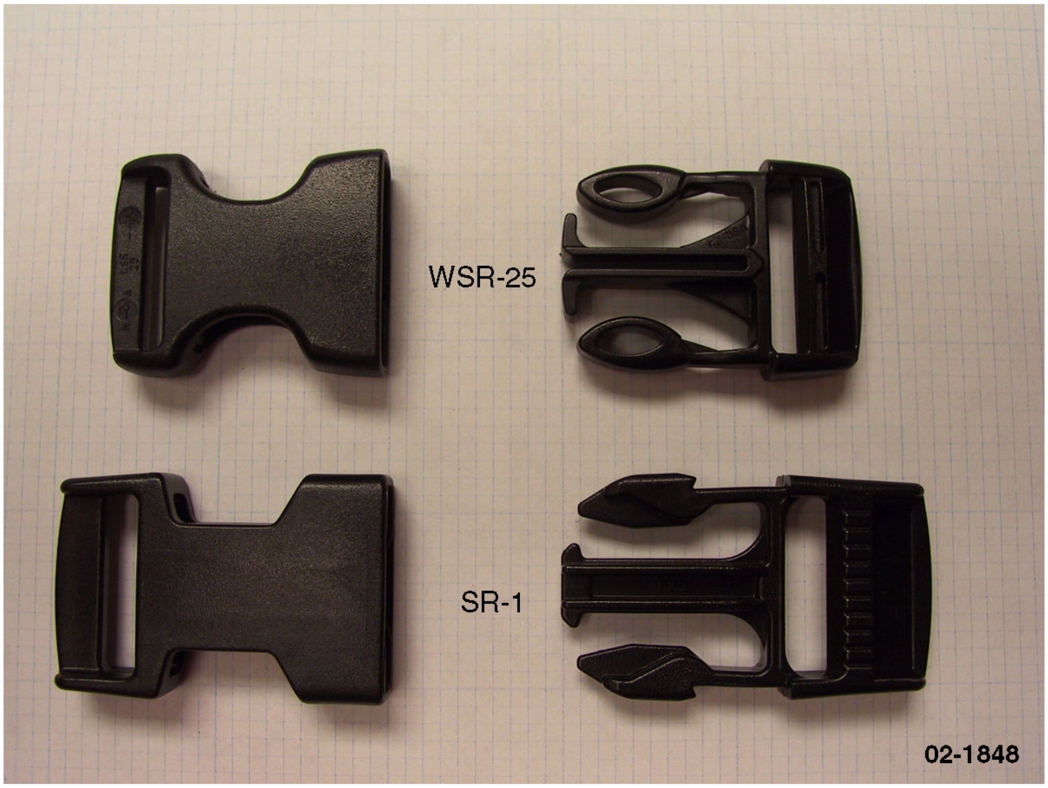


Figure 3. Fastex connector designs

to the sales staff at Fastex, the WSR-25 connector shown at the top was originally designed to replace the SR-1 but was not completed in time to make the Army's cutoff date. The WSR-25 has a more comfortable rounded shape and weighs 20 percent less than the older SR-1.

In order to flesh out certain design concepts, Foster-Miller decided to create a prototype Fastex power bus connection. This connector was intended to be a proof-of-concept and as such was only designed to transmit power. Conductive copper tape was placed on the inner surface of the female connector and around the prongs of the male connector so that when the two connectors were mated, an electrical contact was formed. Wires were then run through the body of the connector and back to the conductive narrow woven textile. The first connector design iteration (Figures 4 and 5) used a narrow woven electrotextile fabricated by C.M. Offray. To improve flexibility this electrotextile bus was fairly loosely woven (see SN 2038 in Table 1). Unfortunately, this loose weave was found to allow broken Aracon filaments to short out the bus. This problem was quickly remedied by using an Aracon power bus with a tighter weave (SN 2036 in Table 1) to fabricate a second cable set (Figures 6 and 7). The prototype power conductors effectively made an electrical connection between the two sides of the connector when snapped in place. Repeated mating and un-mating cycles were performed informally by hand without incident or loss of electrical continuity between the two connectors. Electrical continuity, which is the ability of electricity to flow unimpeded, was assessed using a Keithly ohm meter. The textiles used in both power bus demonstration pieces were developed for BAE systems under U.S. Army Contract No. DAAD16-99-C-1047. The technical point of contact at BAE was Mr. John Pederson and he can be reached at (631) 262-8092.

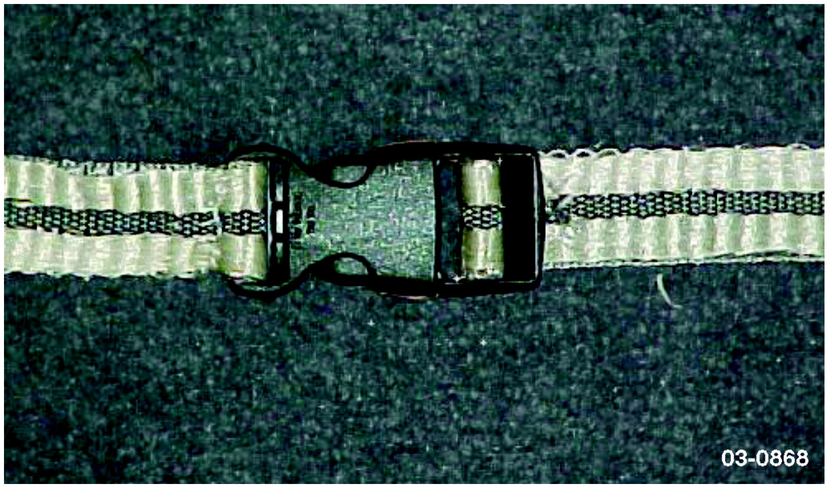


Figure 4. Top view of buckle concept for power transmission using loosely woven Aracon bus

Figure 5. Bottom view of buckle concept for power transmission using loosely woven Aracon bus

Once we successfully showed that power could be transmitted across discontinuous boundaries using a buckle style connector, we took the idea a step further and replaced the center pin of the male buckle connector with a USB type B electrical connector (Figure 8). The corresponding female USB electrical socket was then mounted inside the female half of the buckle connector. To demonstrate the utility of this connector concept, a connectorized USB cable assembly developed for NSC on contract DAAD16-99-C-1016 was cut in half and a modified Fastex connector was attached to each end (Figure 9). The USB electrotextile cable developed under contract DAAD16-99-C-1016 was narrow woven using olive drab 1260 denier nylon yarn at 22 picks per inch (PPI). The electrically conductive elements in this cable included two 22 AWG wires for transmitting power and a twisted pair of 28 AWG wires shielded with foil shielding and stainless steel yarns incorporated into the weave.

Table 1. Details of electrotextile bus construction

Offray SN	2038	2036
Description	Warp Rib 5x5 weave tape with two bands of Aracon separated by Kevlar. The Kevlar sections are a plain weave.	Plain weave tape with two bands of Aracon separated by Kevlar. The Kevlar sections are a plain weave.
Picks/ in.	14	14
Warp Setup	68 ends of Aracon XS0400E-18 (see Appendix A for specs) 8 ends of 1500d Type 970 black Kevlar 68 ends of Aracon XS0400E-18 4 ends of 1500d Type 970 black Kevlar (to hold the edge)	68 ends of Aracon XS0400E-18 8 ends of 1500d Type 970 black Kevlar 68 ends of Aracon XS0400E-18
Filling	1260 denier Nylon	1260 denier Nylon
Catch-cord	System III with Tex 50 black Kevlar	System III with Tex 50 black Kevlar
Width	1 in.	1 in.

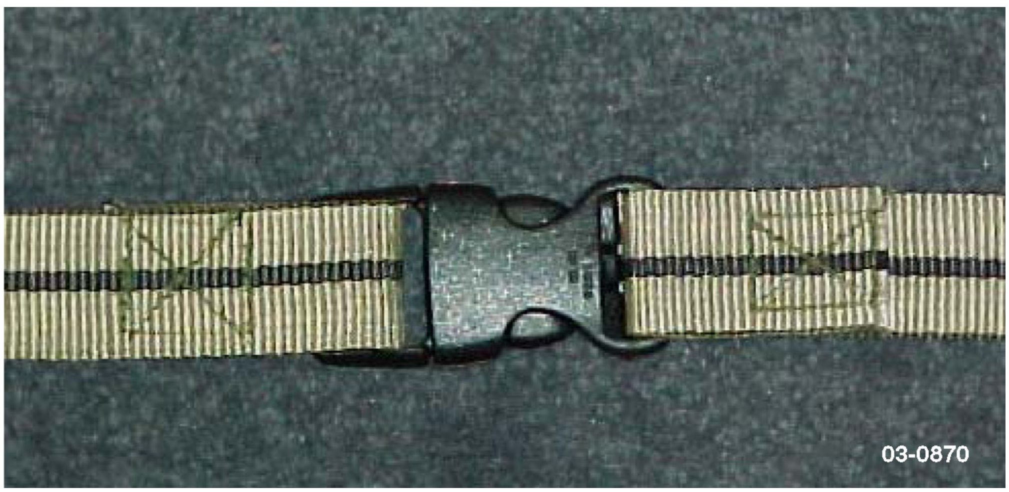


Figure 6. Top view of buckle concept for power transmission using tightly woven Aracon bus

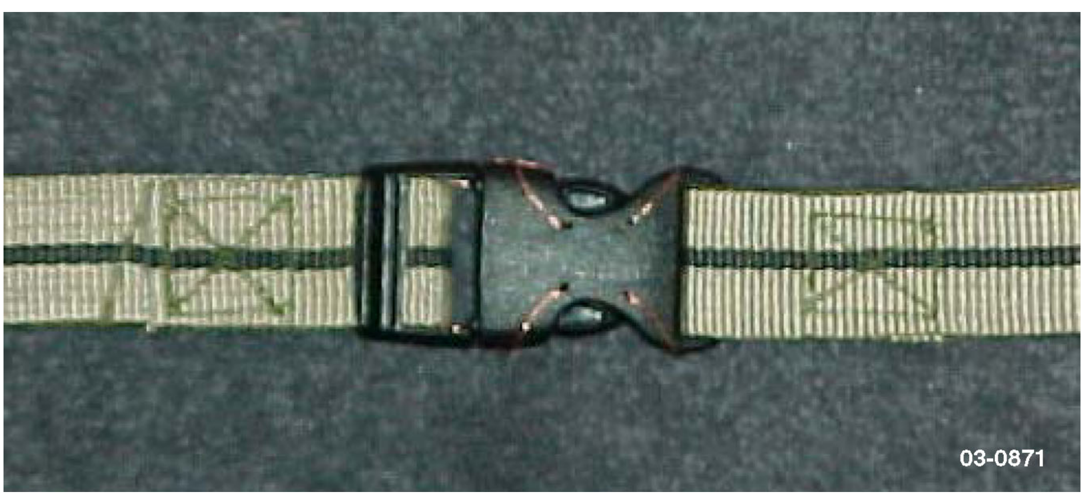


Figure 7. Bottom view of buckle concept for power transmission using tightly woven Aracon bus

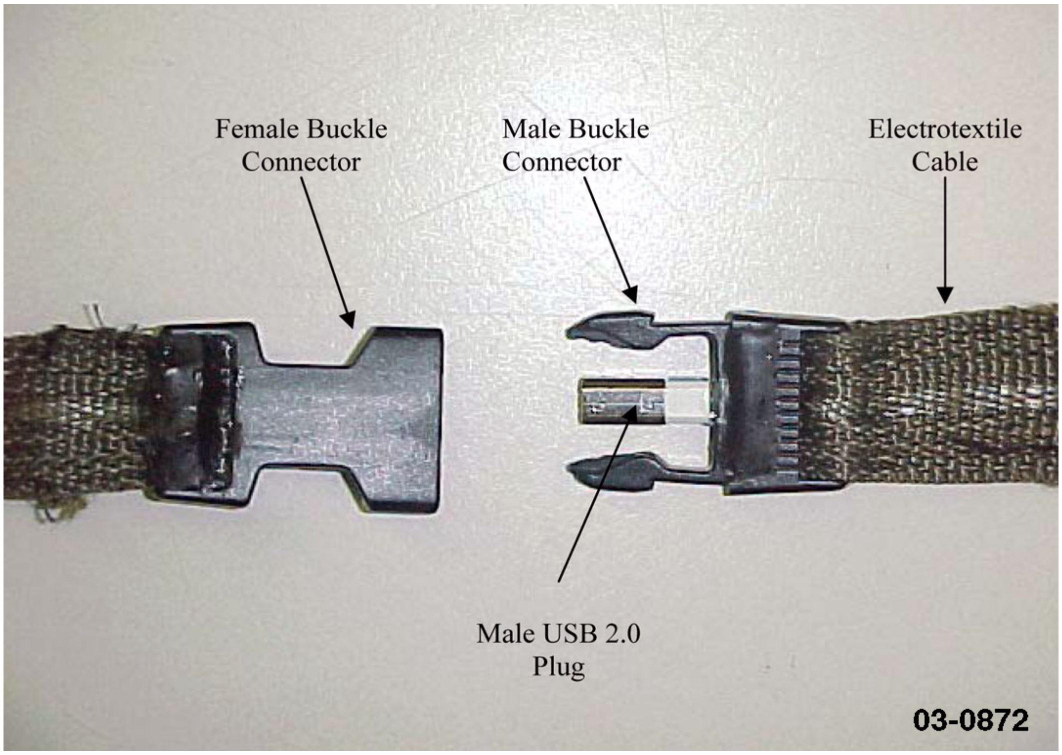


Figure 8. Fastex connector equipped with functional USB plug

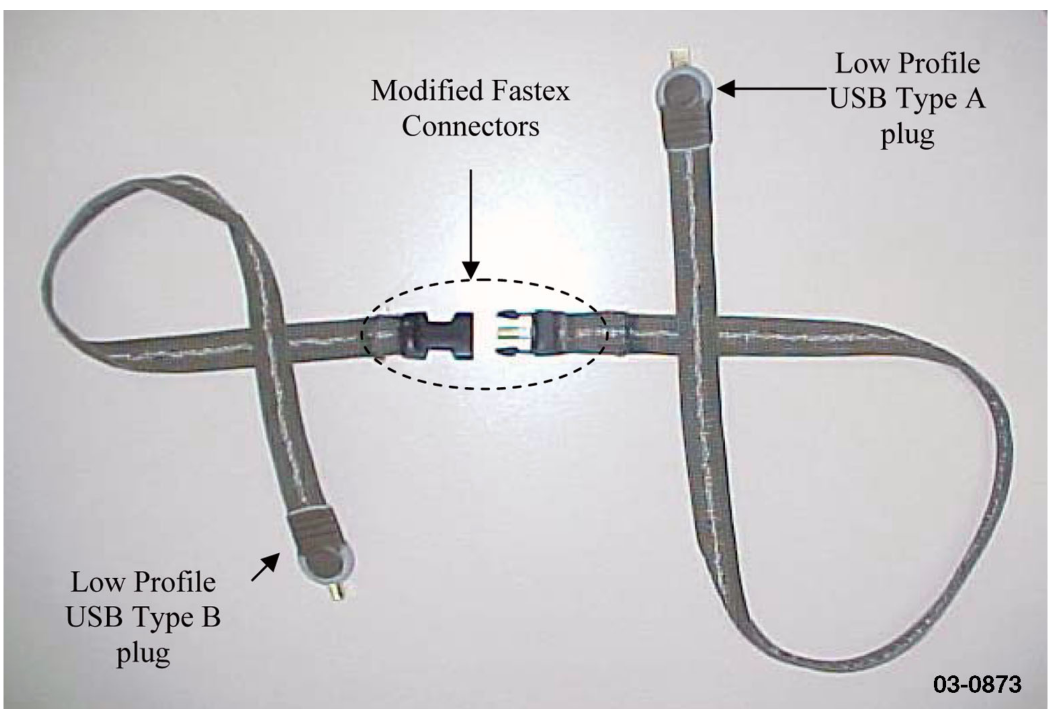


Figure 9. USB v1 cable with Fastex quick disconnect capability for transmission across boundaries

Attachment of the electrotextile cable to the modified Fastex connectors was accomplished by pulling the wires out of the woven cable, approximately 2 in. from the cut. This procedure allowed the wires to then be soldered to the USB plugs while the end of the textile cable was fed through the Fastex connector and sewn to itself. The resulting cabling assembly was fully functional and due to its construction was very rugged. The resulting cabling assembly was successfully demonstrated at the Interactive Textiles conference in Boston and the International Symposium on Wearable Computing (ISWC) conference in Seattle. During these demonstrations, the cable was shown downloading streaming images from a digital camera to a laptop. Throughout the two shows and other demonstration, the Fastex connector was manually connected and disconnected in excess of 100 times without incident.

It quickly became apparent that while functional, USB connectors would not be sufficiently rugged for military field applications. After discussions with the Army and Plastics One, it was determined that we would use the same 5-pin 0F Lemo connector that was then being used on the Land Warrior 1.0 system. The 0F Lemo connector was selected due to its small size and relatively high pin count as compared with the USB connector. When mated, this connector has an environmental protection index of IP67 as per the BS 5490; IEC 529 standard. This British Standard Specification provides a system for classifying the degrees of protection provided by an enclosure. The designation to indicate the particular degrees of protection consist of the letters IP followed by two numerals. The first numeral indicates the degree of protection against the ingress of solid foreign objects. The second numeral indicates the degree of protection against the ingress of water. The rating of IP67 for instance indicates that when mated the 0F connector is guaranteed by LEMO to be dust tight and protected from temporary immersions. Our inspection of the 0F Lemo revealed that much of the connector’s bulk comes from its latching mechanism. Since the Fastex buckle connector takes up this functionality, we initially proposed that this portion of the Lemo (Figure 10) could be removed. The stripped inner barrel of the 0F Lemo is shown in Figure 11 next to a proposed buckle connector.

While the stripped down Lemo approach would reduce connector volume and transfer latching functionality to the buckle, it also removed most of the connector’s water resistance in the process. Another concern with the latching mechanism on the 0F was that even if it were left intact to maintain its environmental protection, it would still need to be overmolded. This procedure would immobilize or at least restrict the range of motion of the outer release sleeve of the latching mechanism, leading to an undesirable increase in the required pullout force. Pullout tests performed with a 0F connector overmolded on another program (DAAD16-02-C-0006) indicated that pullout force varied erratically depending on the alignment of the latches and how well they were mated.

To address these issues, a COTS connector that has a high environmental protection index and does not incorporate a fixed latching mechanism was sought. After discussing this issue at a meeting with the Army and Exponent, Exponent suggested that we try a 0K series Lemo connector. While significantly larger than the 0F (Figures 12 and 13), it was thought that the 0K did not incorporate a mechanical delatching mechanism and could be automatically decoupled with a 10 lb pull. This lack of a latching mechanism was to be key in allowing the 0K to be directly integrated into the buckle connector without having to be disassembled. With a

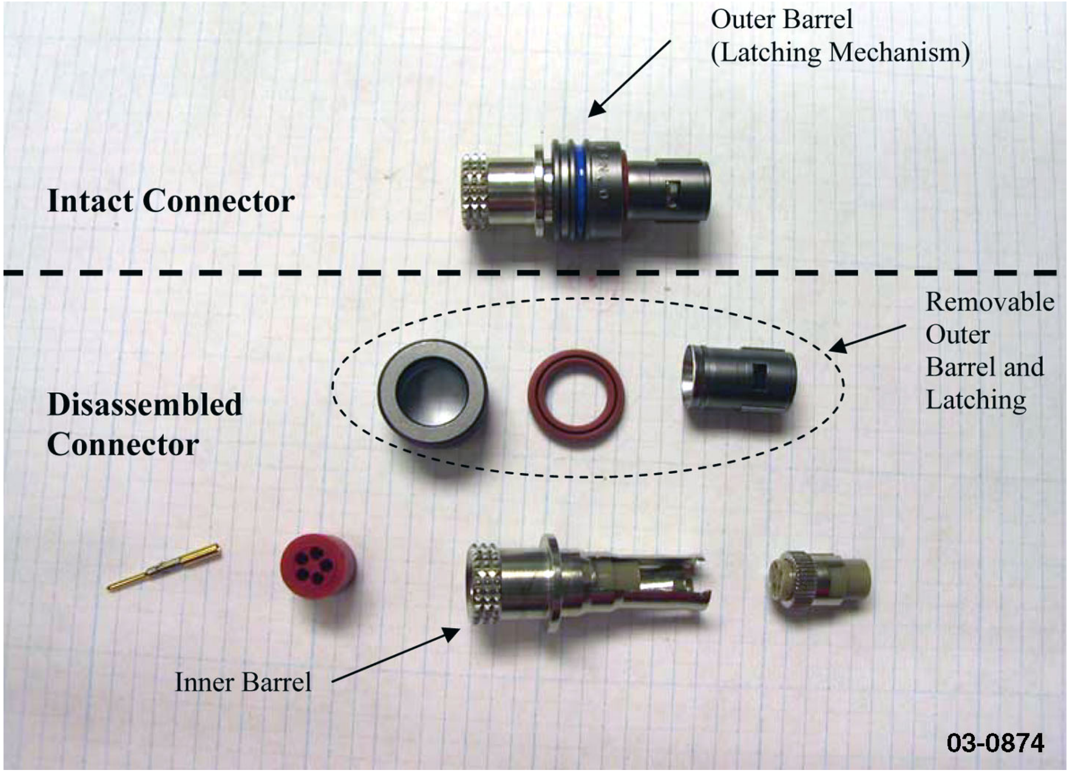


Figure 10. Intact and disassembled 0F Lemo connector

Figure 11. Buckle connector shown with inner barrel of 0F Lemo connector

manufacturer specified rating of IP66, the K series was also able to provide a level of environmental protection similar to that of the F series.

Eagle Design & Technology was commissioned to generate Computer-Aided Design (CAD) files and Steriolithography (SLA) models of the two different Fastex connector designs under consideration. These CAD files were needed to reverse engineer the connectors and then modify them to support electrical functionality. The CAD drawings generated by Eagle are shown in

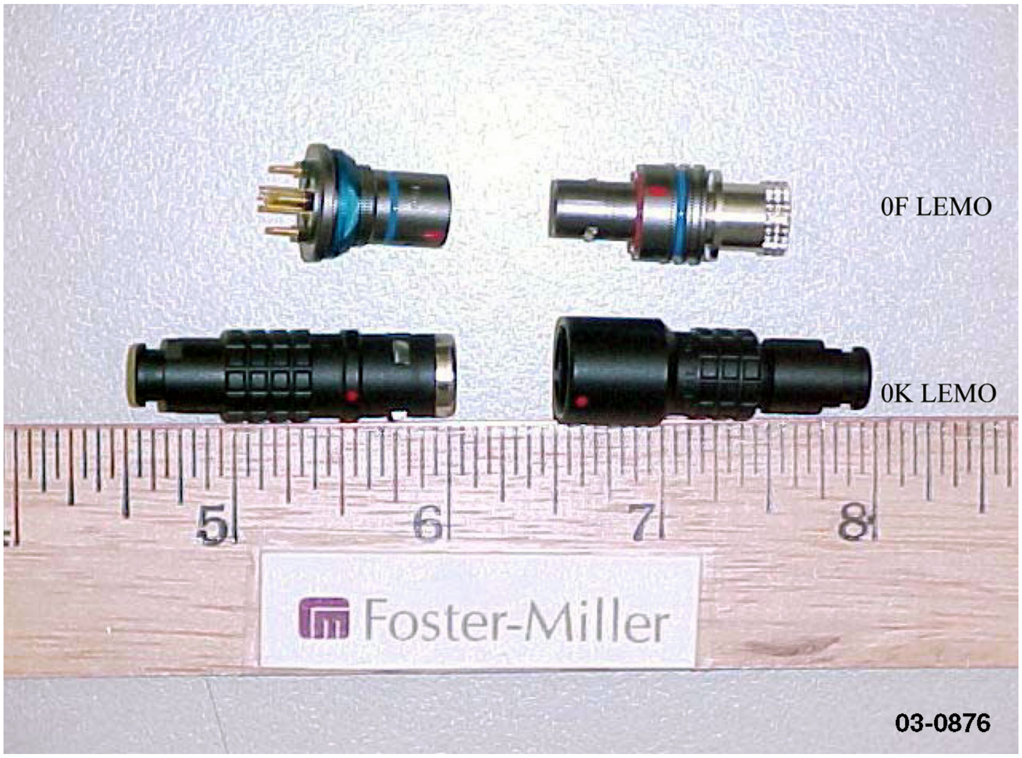


Figure 12. Unmated 0F Lemo and 0K Lemo shown at top and bottom, respectively

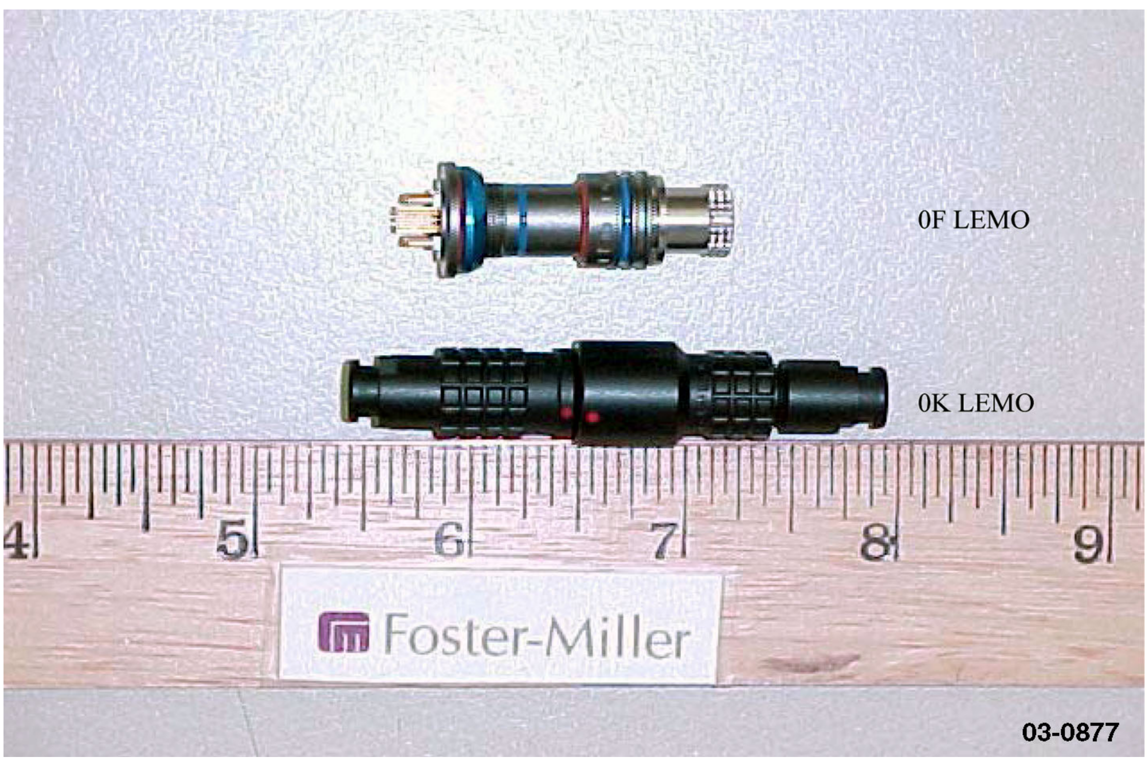


Figure 13. Mated 0F Lemo and 0K Lemo shown at top and bottom, respectively

Figures 14 and 15, and the SLAs are shown in Figure 16. The CAD drawings of these four Fastex connector components were then sent to Plastics One. Mr. Barry Brindle of Plastics One modified these files to create Fastex style connectors that supported 5-pin 0K Lemo connector functionality. Due to its rounded ergonomic shape and more efficient use of material, it was decided that we would use the WSR-25 in our initial prototyping efforts. Figure 17 shows the 0K connector inserted directly into the WSR-25 connector without modification. This figure shows that in order to accommodate the entire 0K Lemo connector the buckle had to be extended in length, width and thickness. The webbing straps were also removed and replaced with a solid section that encapsulated the narrow woven electrotextile. As can be seen from Figures 18 and 19 the resulting connector was significantly larger than originally envisioned with a length of nearly 6 in. To reduce the connector's length, the threaded end caps were replaced with much

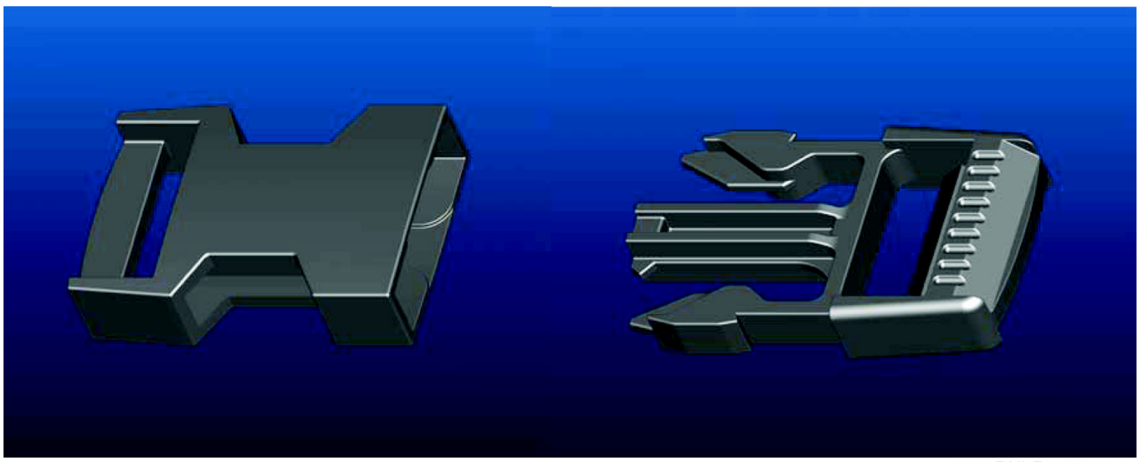

617-DNLB-020100-1

Figure 14. SR-1 Fastex clip

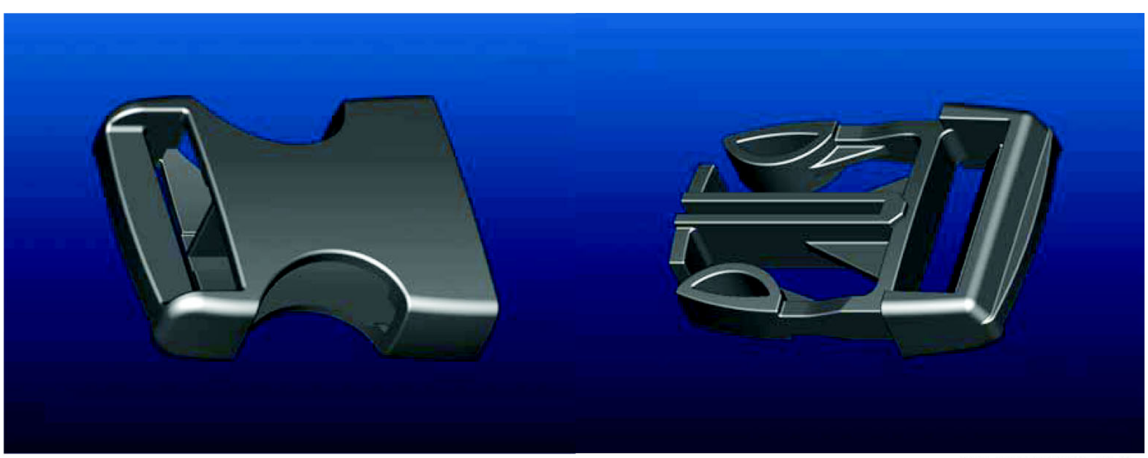

617-DNLB-020100-2

Figure 15. WSR-25 Fastex clip

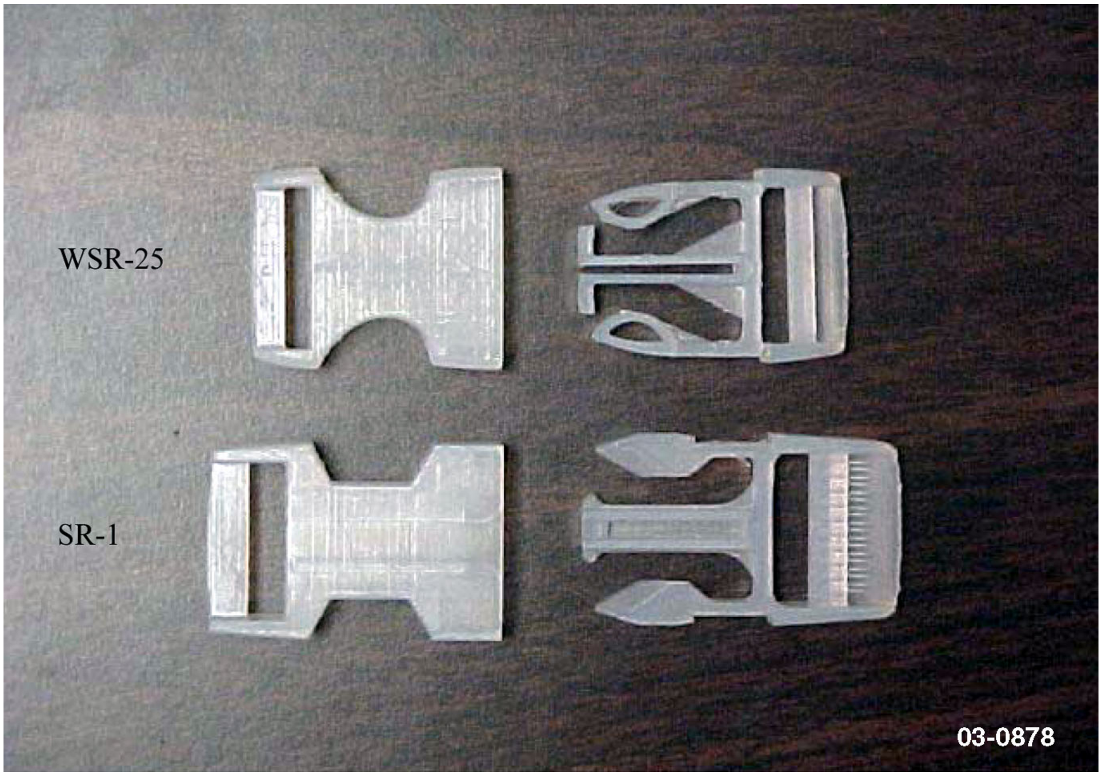


Figure 16.   SLAs of SR-1 and WSR-25 Fastex connectors

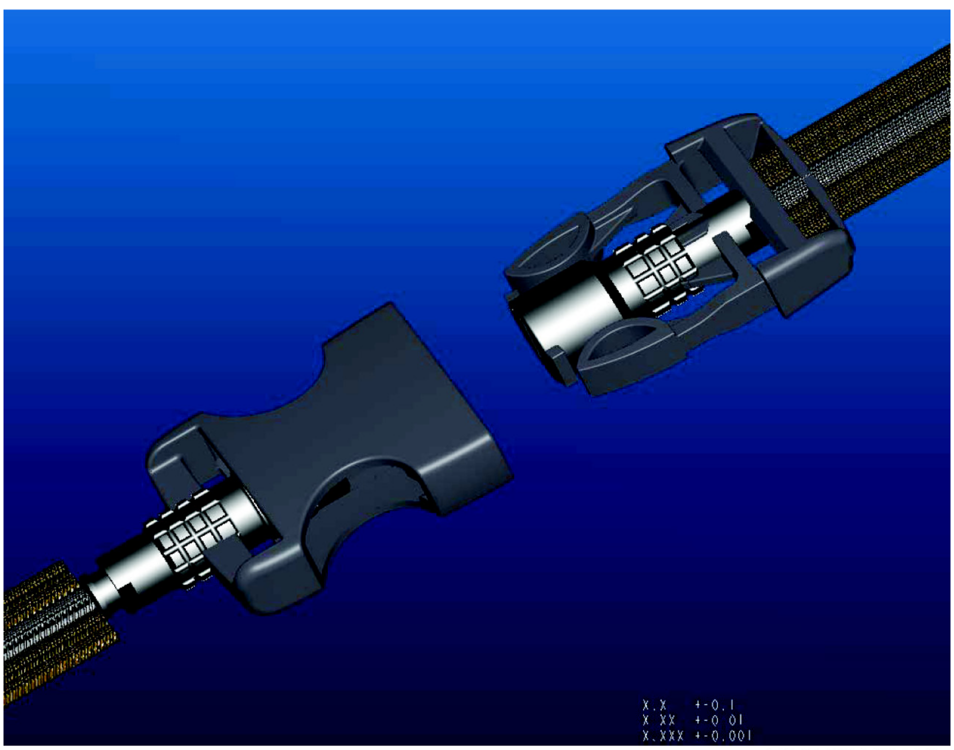
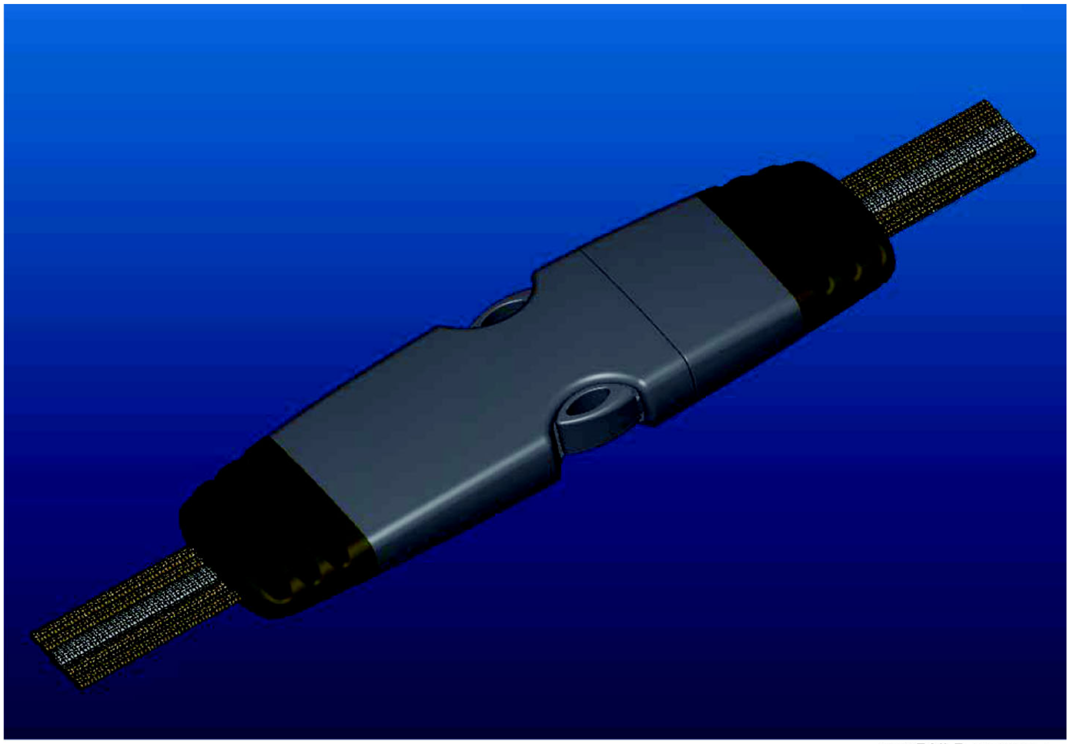


Figure 17.   0K Lemo connector and 3/4 in. wide textile cable inserted directly into unmodified WSR-25 connector for evaluation purposes only



617-DNLB-020100-4

Figure 18. First attempt at completely enclosing 0K Lemo connector using WSR-25 connector as a baseline

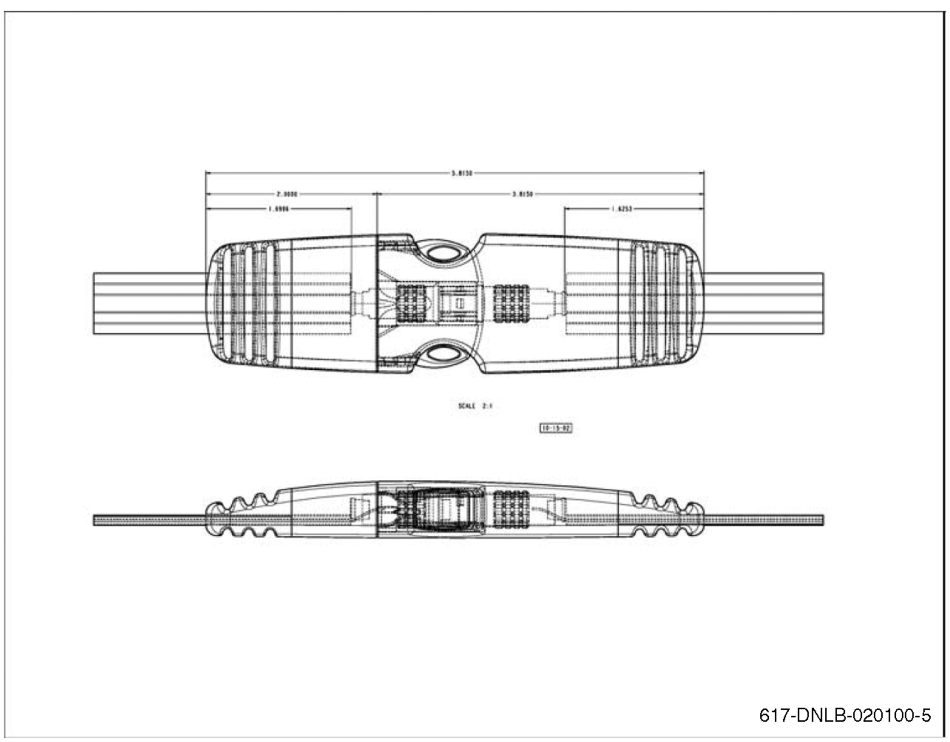


Figure 19. Schematic of first attempt at enclosing 0K Lemo connector using WSR-25 connector as a baseline

shorter slotted end caps (Figure 20). Not only did this modification reduce the length of the 0K connector but it also eliminated the need to have excess exposed wiring during connectorization (Figure 21). This in turn reduced the amount of textile cable that needed to be overmolded. The net effect of these changes was to reduce the overall length of the connector by approximately 1-1/2 in. (Figures 22 through 25). SLAs were made using this design (Figure 26 and 27) and then connectorized using the previously described cable developed on Contract No. DAAD16-99-C-1016 (Figure 28). While this shortened connector concept was an improvement over the 6 in. version, it was felt to be too large for use into the Scorpion Bravo ensemble. Due to perceived difficulties in integrating this buckle connector, a decision was made by all parties to not pursue its development past the current prototyping stage. Despite these limitations, it is felt that this connector concept has many applications in commercial products where bulky waterproof inserts are not needed.

3.2.2 Other Connector Concepts

Dovetail Connector

One of the other two original connector concepts investigated during this program was a sliding dovetail interface (Figure 29). This interface is currently used by police and SWAT teams to connect the antenna to the radio. It has previously been shown to withstand the relatively harsh conditions seen by police in the field. This design securely attaches the electronics device to the body and provides redundancy using two sliding dovetail connections.

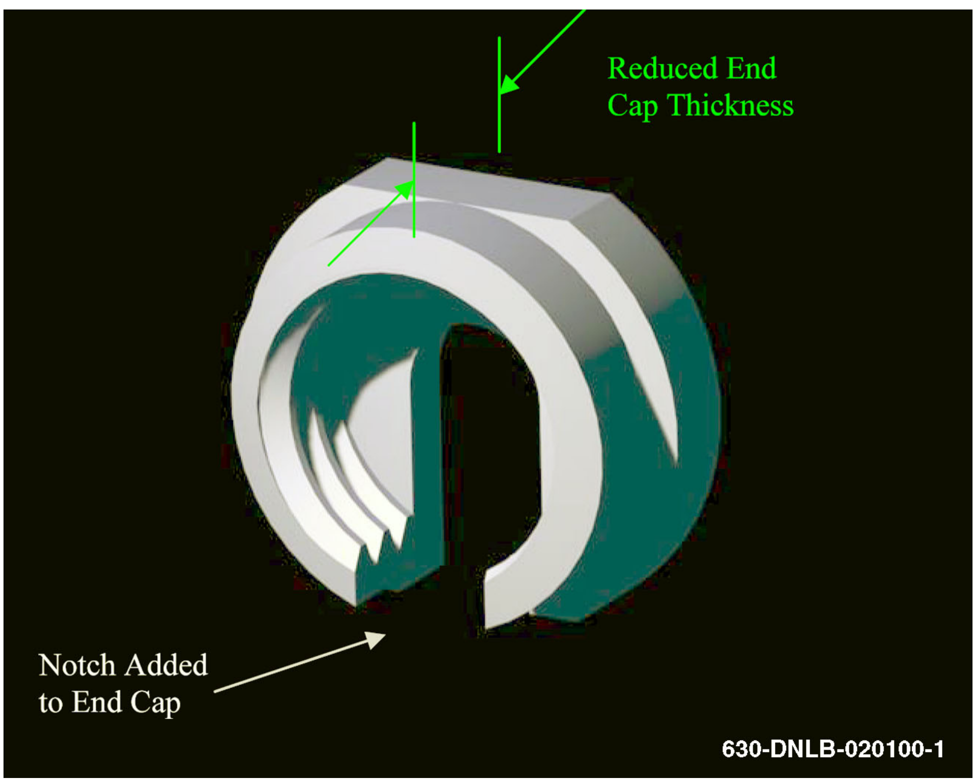
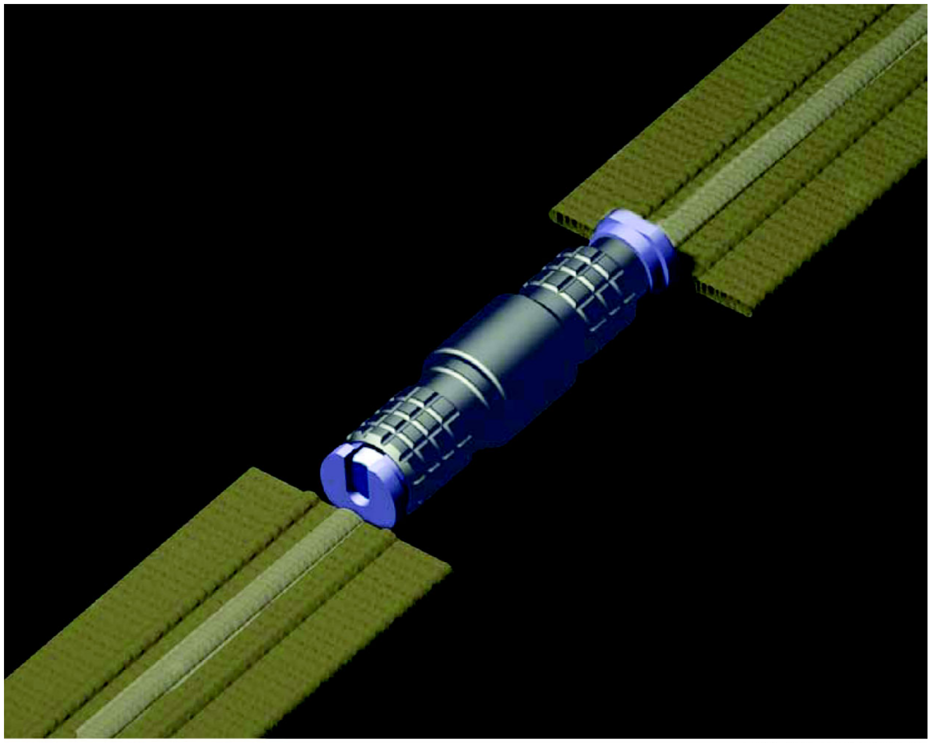
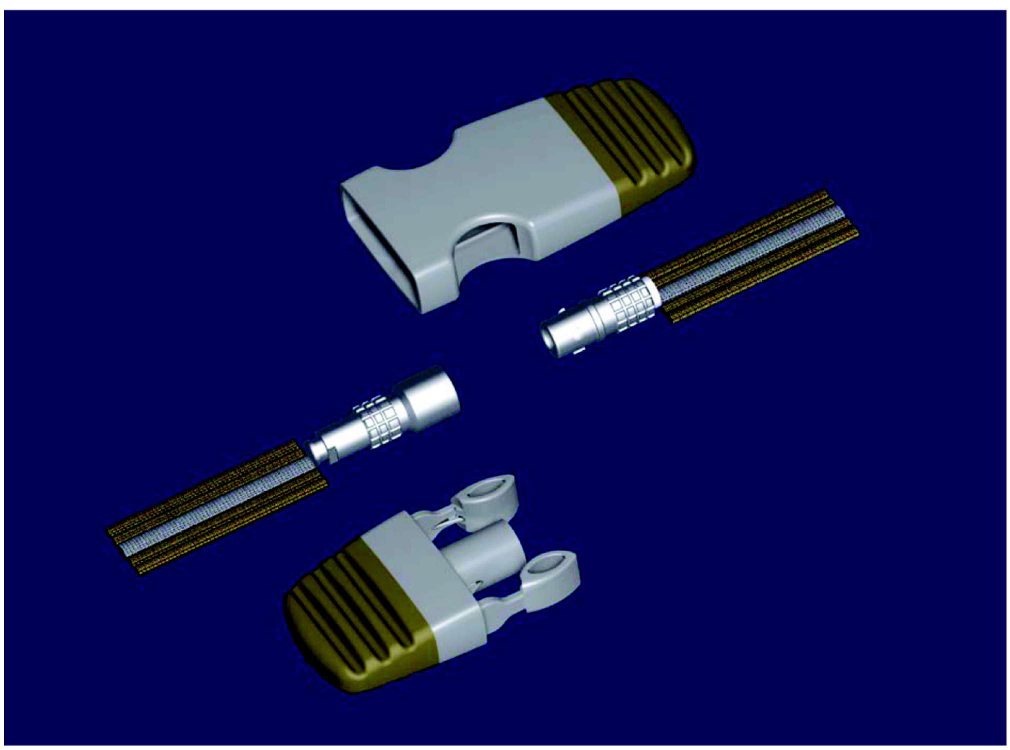


Figure 20. Shortened and notched end-cap



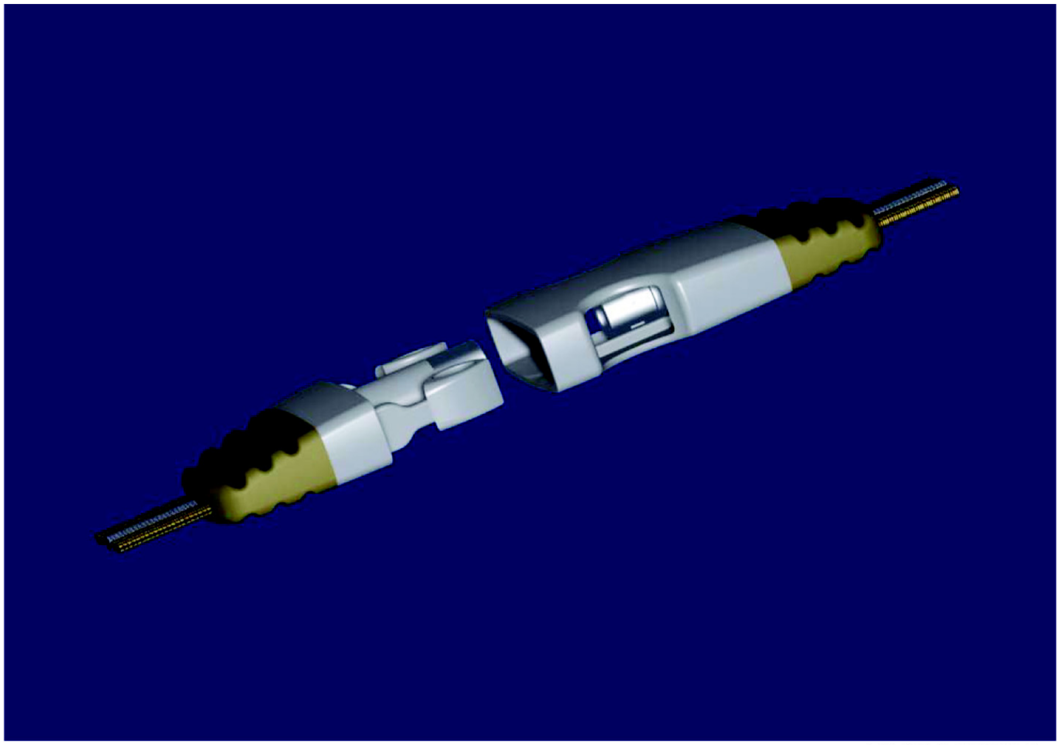
617-DNLB-020100-7

Figure 21. Shortened connector assembly



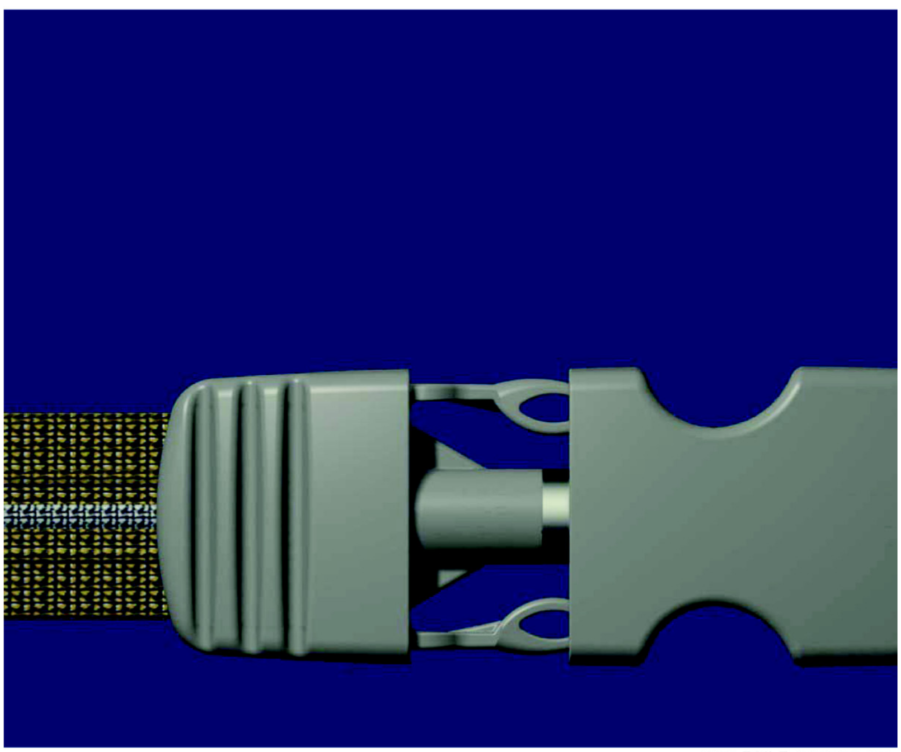
617-DNLB-020100-8

Figure 22. Shortened connector assembly and connector overmolding



617-DNLB-020100-9

Figure 23. Redesigned buckle connector



617-DNLB-020100-10

Figure 24. Redesigned buckle connector

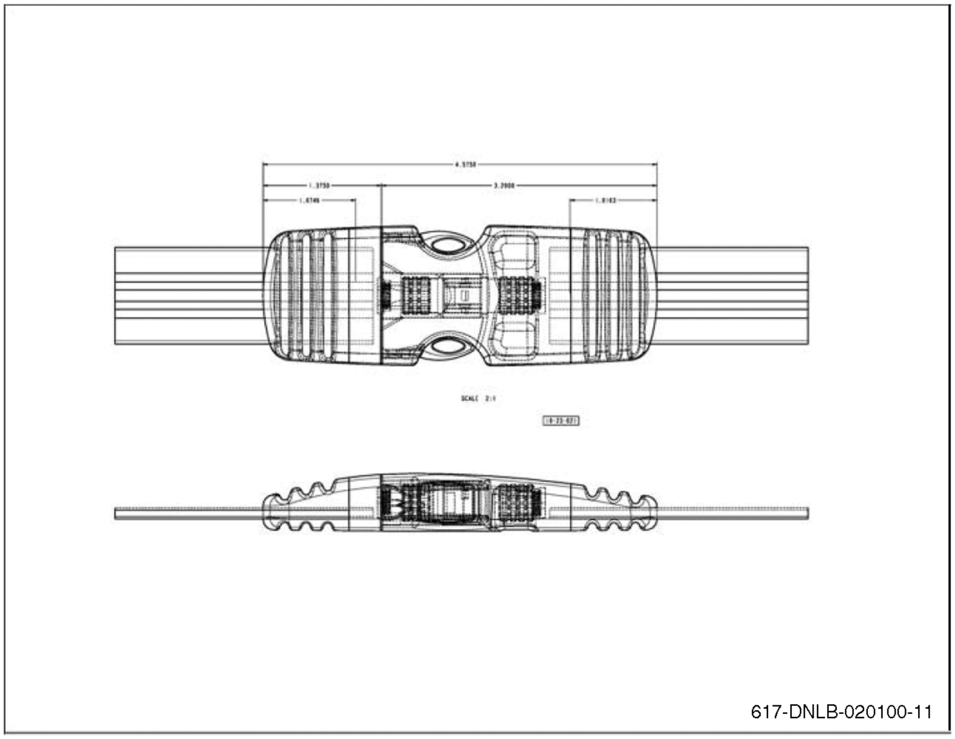


Figure 25. Schematic of redesigned buckle connector

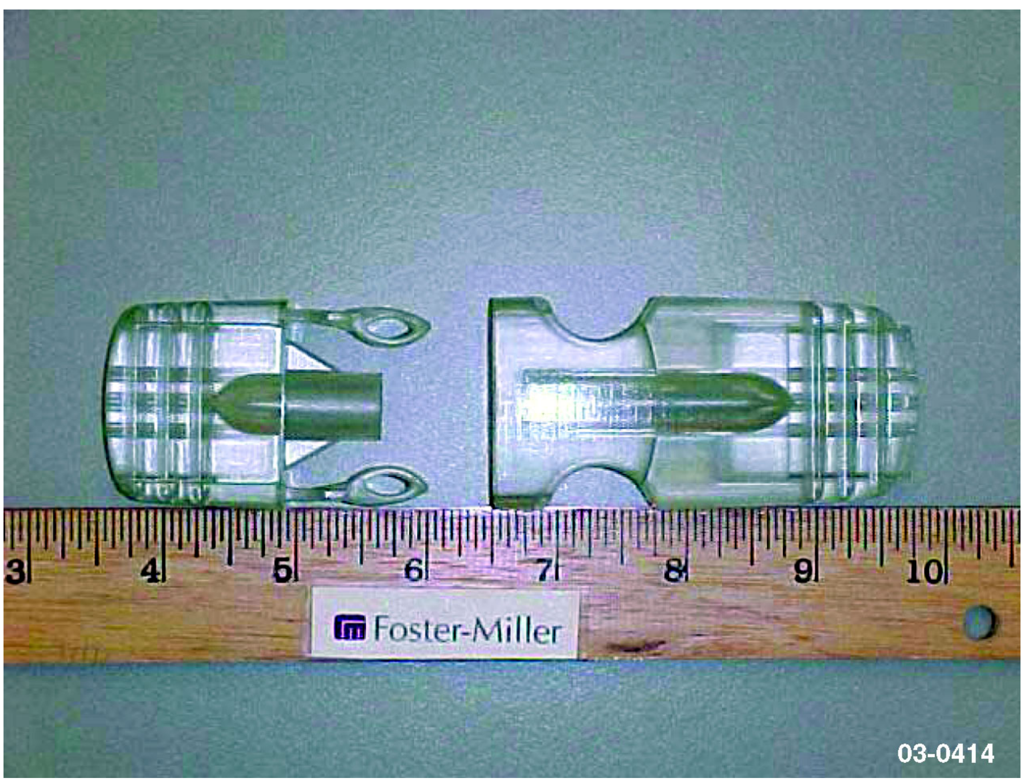


Figure 26. SLA of redesigned buckle concept

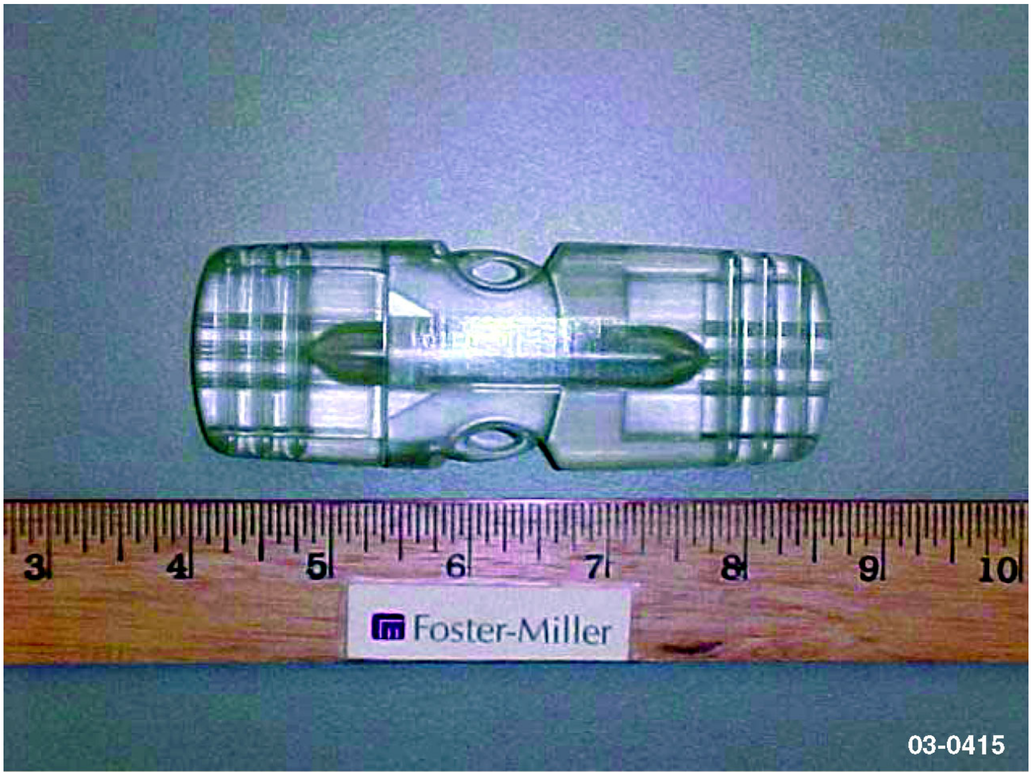


Figure 27. SLA of redesigned buckle concept

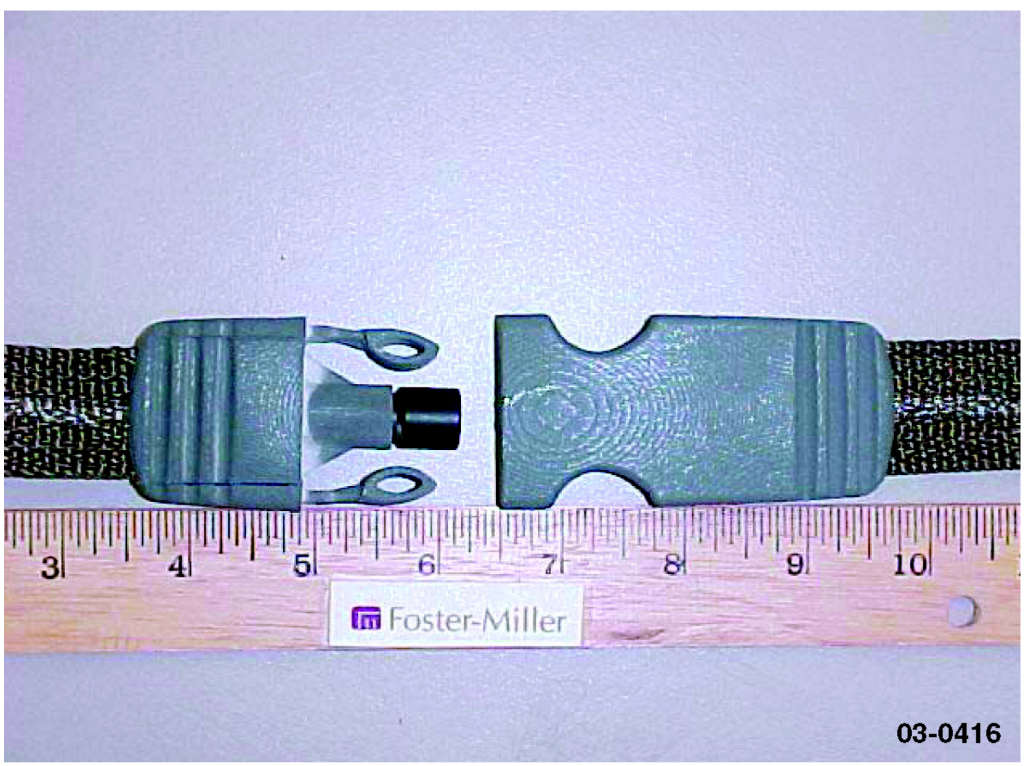


Figure 28. Functional SLS of buckle connector concept using 0K Lemo

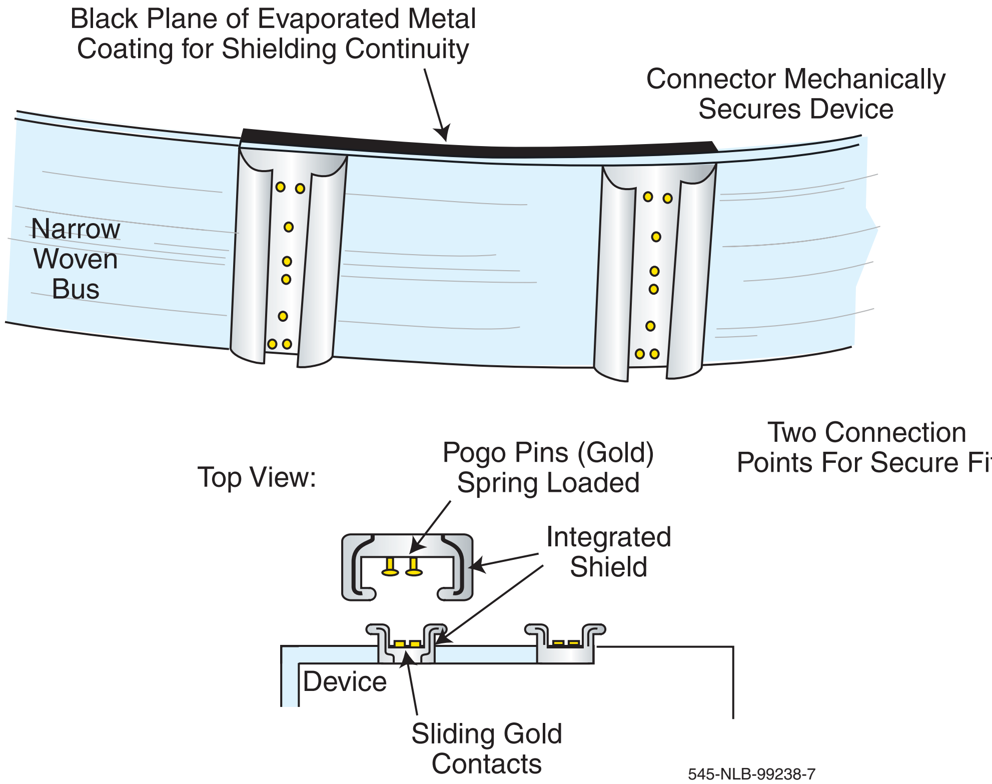


Figure 29. Dovetail concept

Based on discussions with Plastics One and Natick, it was decided that this design concept would be pursued first. [Note: This decision was made prior to the SOW modification, and was changed as a result of the contract modification.]

It was envisioned that this connector be used to attach a system of replaceable pods, similar to those developed at Carnegie Melon (Figure 1), to an electro-textile cable substrate (Figure 29). These pods could contain batteries, computer modules, sensors and various other electronics packages. During brainstorming sessions with Barry Brindle, Plastics One's lead design engineer, it was determined that this connection mechanism would be extremely difficult to waterproof due to the sliding action inherent in the design. The shear forces generated by this motion would damage or dislodge any gaskets or O-rings used to seal the system. To address these issues, a snap/latch mechanism was proposed. This approach calls for a module to snap into place on a rigid back plane in much the same manner that a battery snaps into a cell phone (Figure 30). This motion allows the O-ring to be firmly compressed without generating any damaging shear forces. In this concept, the back plane is overmolded onto a data/power cable substrate. If necessary, a latching mechanism may be added over the entire assembly to further ruggedize and secure the connection. When grouped together, the pods lie along a curving arc (Figure 31) that conforms to the wearer's body. This approach may necessitate weaving discrete lengths of data cable that are inherently curved rather than straight. One drawback to this kit approach to assembly is that it would be more expensive than buying straight data cable as a rolled good.

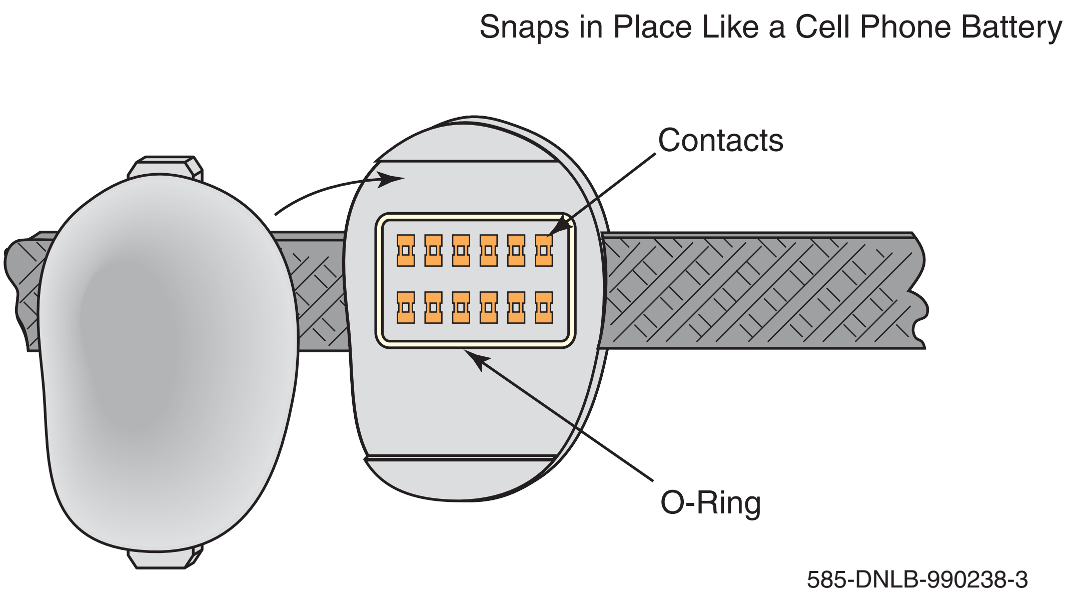


Figure 30.   Snap/latch style connector

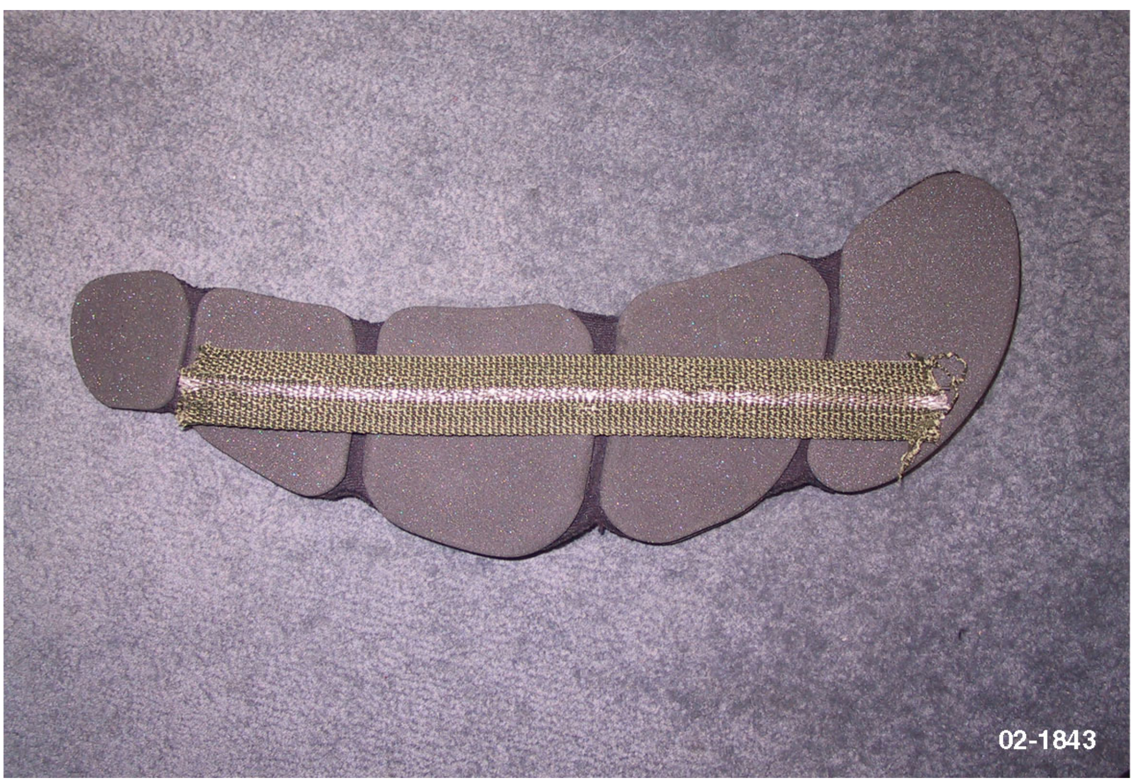


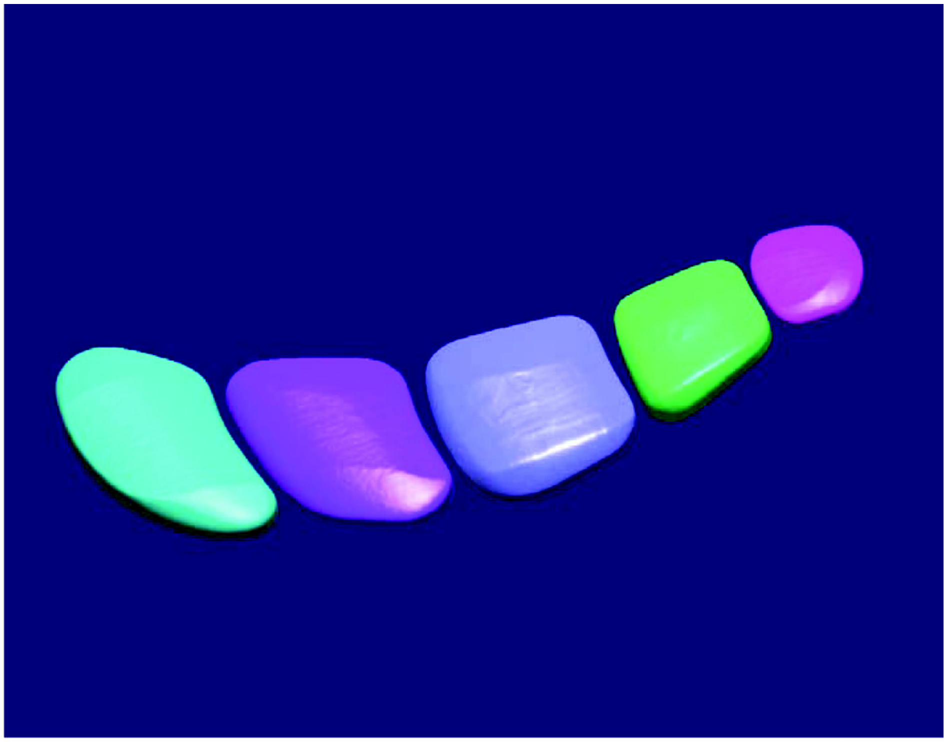
Figure 31.   Collection of pod forms shown with narrow woven textile cable

Once the change in the general design approach was authorized by the Army, Foster-Miller obtained the original pod forms from Carnegie-Mellon. Pictures were taken of the pods and sent to Eagle Design & Technology to be appraised for scanning and CAD file generation. It was determined that the black absorptive surface of the foam pods could not be scanned in their current form (Figure 31). The scanning process used by Eagle requires a minimum amount of laser light to be reflected and registered in order to generate a 3-D image of the part. In order to increase the pods' reflectivity, they were sprayed with hair spray and then coated with talcum powder (Figure 32). The coated parts were then sent to Eagle for scanning.

Using the CAD drawings generated by Eagle Design (Figure 33), SLA demonstration pieces were made (Figure 34). These prototypes were useful in assessing three-dimensional shape concerns.

To assess the suitability of straight cables for this contoured application, it was decided to fabricate the entire bus-connector interface using the prototype pods, adhesives and sections of the USB buses fabricated on the separate ongoing Phase II program (DAAD16-99-C-1016). To asses various latching mechanisms, we decided that a set of foam "devices" would be shaped and outfitted with the corresponding mate connector. These three-dimensional prototypes would then be used to try out the mechanics of mating and de-mating the connectors on a garment. Before these actions could be pursued further, the scope of the program was altered and it was determined that the Army had no near-term desire to pursue the latching connector concept further on this program.

Figure 32.   Pod form coated for better reflectivity



617-DNLB-020100-12

Figure 33. CAD files generated from scans of pods

Figure 34. SLAs of pod forms from wearability study

Snap Connector

Figure 35 depicts the snap interface connector concept originally envisioned for this program. This concept is an extension of flush contacts manufactured by Plastics One and used for many electrode connections (Figure 36). Unlike conventional snaps, the proposed snaps have a spring clip in the socket to ensure electrical contact and to increase the mechanical load required to detach the snap. The advantages of this concept are:

- Ability to use several snaps in a non-symmetrical pattern to ensure correct attachment.
- Ease of attachment to the device.
- Familiarity to the user.
- Ability to attach the device at multiple points so that it feels like part of the user's clothing.
- Ability to bridge non-connected interfaces within the soldier ensemble.

Discussions with Mr. Barry Brindle of Plastics One revealed that they had difficulty in developing a similar line of snap connectors for the medical monitoring field. Figures 37 through 40 show the connectors developed by Plastics One during this effort.

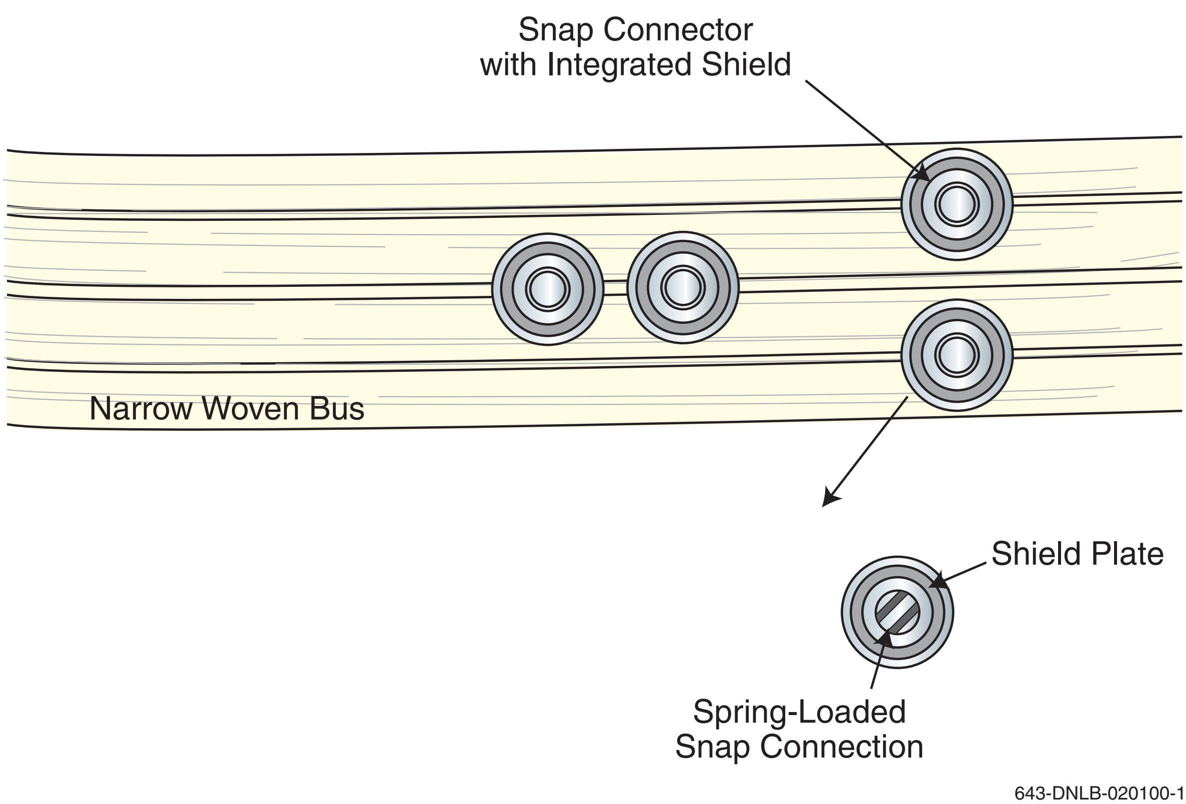


Figure 35. Snap connector concept

Figure 36. Monopole snap connectors from Plastics One shown with Foster-Miller Aracon power bus

Figure 37. Male portion of the Plastics One dipole snap connector

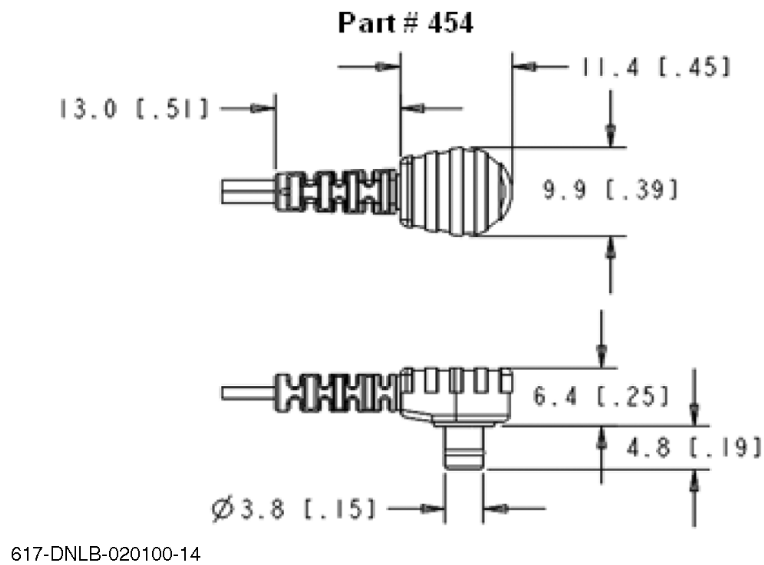


Figure 38. Schematic of the male portion of the Plastics One dipole snap connector

Figure 39. Female portion of the Plastics One dipole snap connector

One advantage of these connectors was that they could transmit shielded data while being rotated a full 360 deg, a potentially useful capability for wearable application. While these connectors have a larger form factor than that envisioned by Foster-Miller, they provided a good starting point for further development.

Discussions with Army personnel revealed that during field exercises external snap connectors were prone to plug up with mud and detritus, rendering them inoperable until cleaned. Based on these findings, Foster-Miller decided to delay producing the snap connector prototype until the issue could be looked at more closely. Before this issue could be addressed

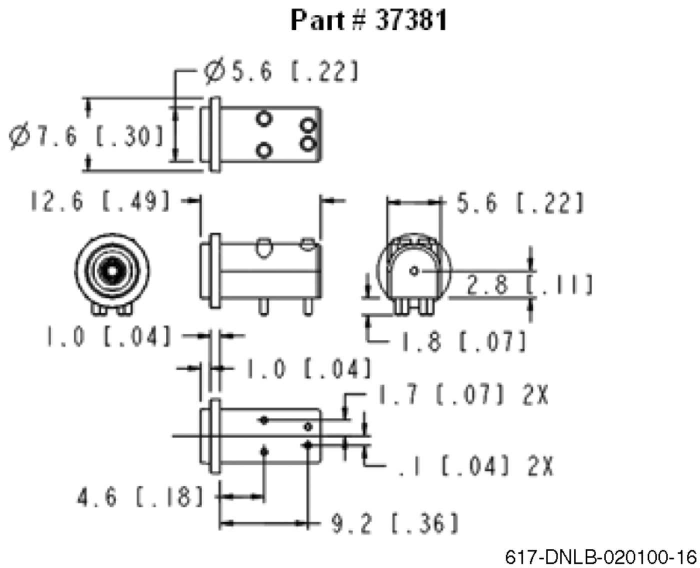


Figure 40. Schematic of the female portion of the Plastics One dipole snap connector

further, the scope of the program was altered and it was determined that the Army had no near-term desire to pursue the snap connector concept further on this program.

3.3 Task 4 - Ergonomic Evaluation and Refinement of Connector Designs

The prototype connector developed in Tasks 2 and 3 was presented to the Army and team members working on the Scorpion Bravo system during a meeting at Natick. One of the immediate concerns was over the connector's length. At 4.5 in., the connector was felt to be too long to be effectively integrated into the soldier ensemble. Not only would the integration site need to accommodate this length but it would also need to allow a certain amount of room for travel during latching and unlatching. Despite efforts to make the connector body smooth and rounded and to incorporate bend relief into the overmold, it was felt that the sheer size of this connector design made it unacceptable from an ergonomics standpoint.

Another concern was the manner in which this design attempted to prevent incorrect mating. As shown in Figure 41 this system used a small key in one corner of the connector which mated with a groove on one of the mating connector's clips. It was found, however, that when improper connector mating was attempted the key would simply push the clip out of the way if no groove was available. The connectors could then be forced together until the Lemo connectors came into contact. At this point, the Lemo connectors themselves prevented further mating. While it was not possible to make an improper electrical connection, this ability to improperly mate the connectors from a mechanical standpoint was still a problem. Correcting the connector mating mechanism proved to be the easiest issue to address. The keying mechanism was moved from the connector clip to the center portion of the mechanism, adjacent to the Lemo connector (Figures 42 and 43). In the new configuration, incorrect mating of the connectors is possible.

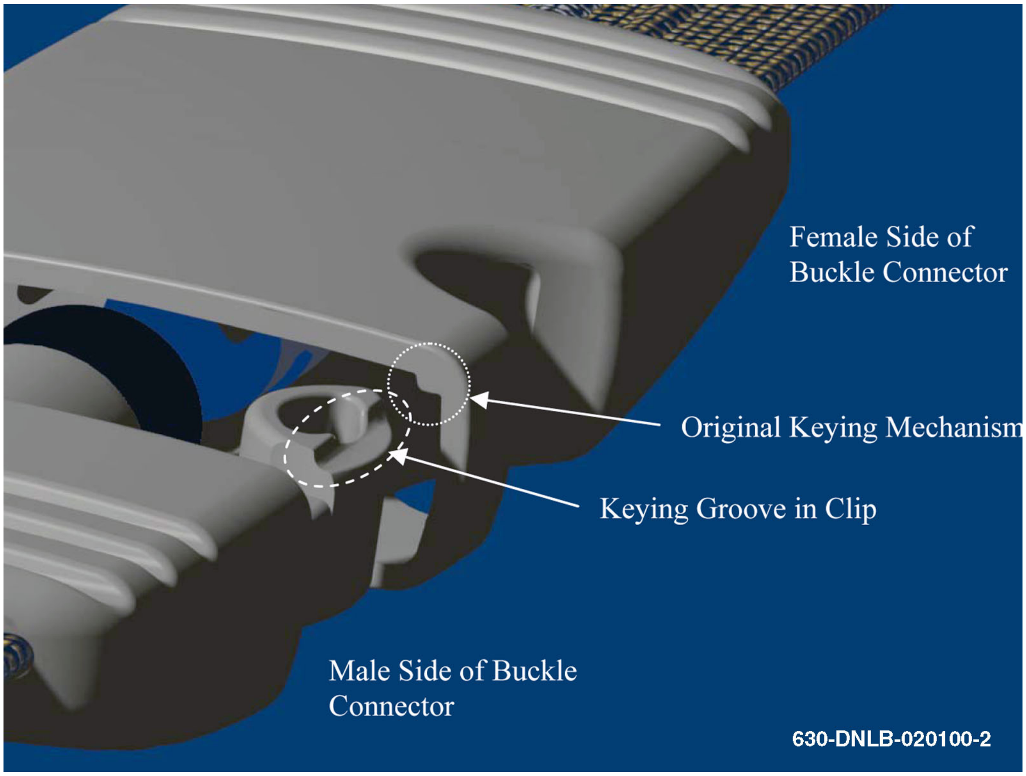


Figure 41. Original keying mechanism with keying groove located on connector clip

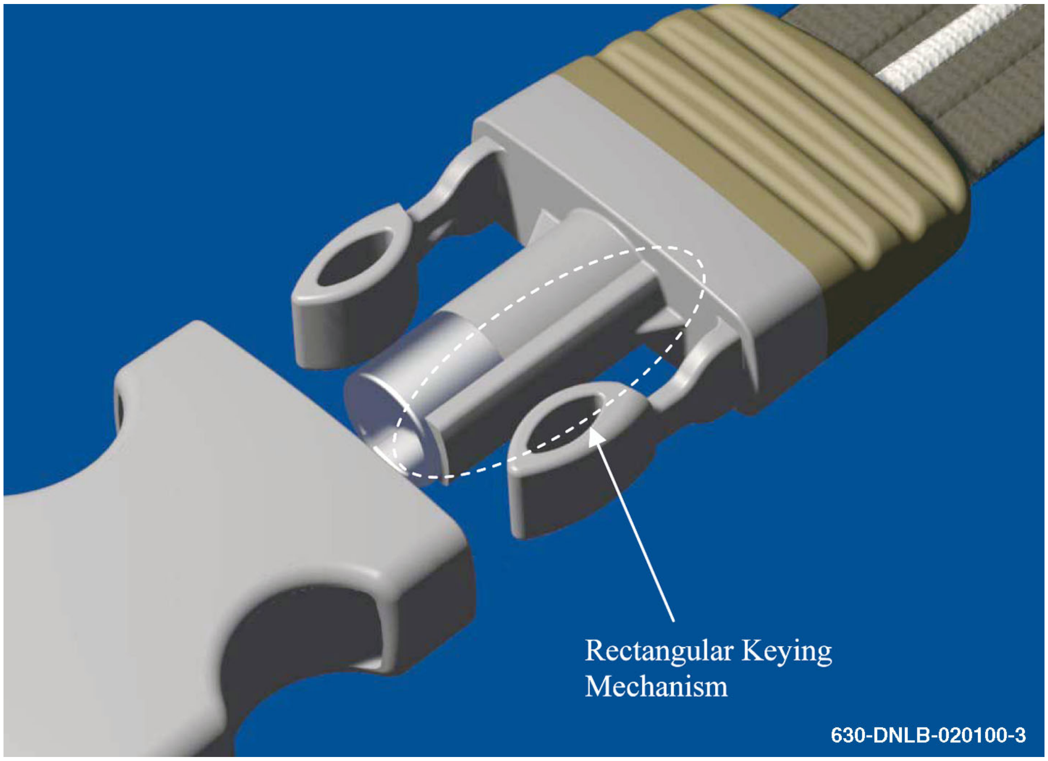


Figure 42. Improved keying mechanism with key located on barrel of the Lemo connector

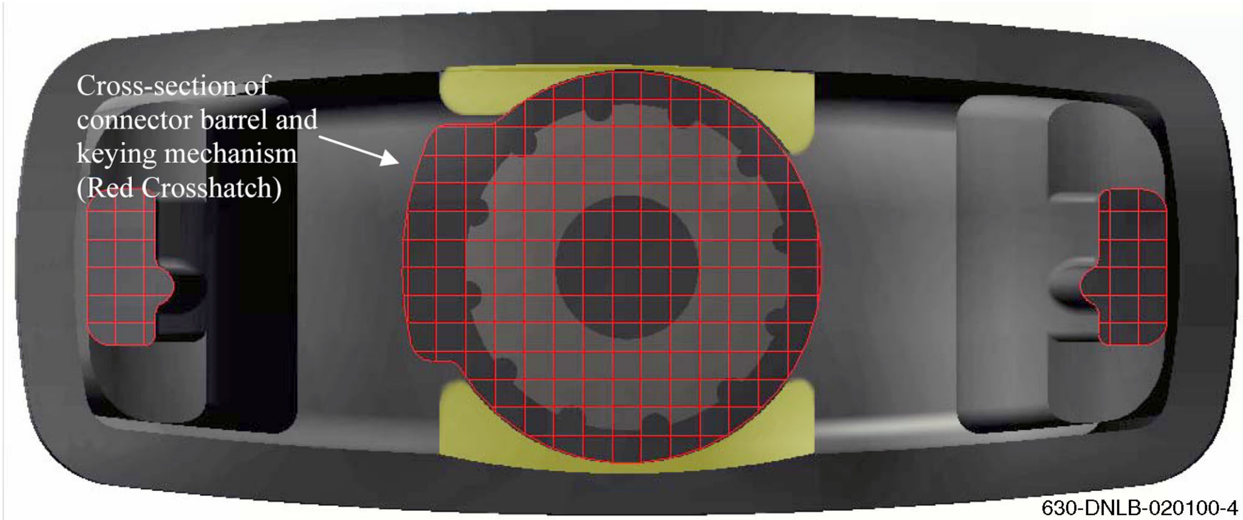


Figure 43. Cross section of improved keying mechanism

Shrinking the dimensions of the buckle connector below the 4.5 in. currently attained will take continued effort. One realization that came late in the program was that the 0K connector had a latching mechanism similar to that of the 0F. This was not recognized at first as the sleeve design made it almost impossible to not engage the delatching mechanism when pulling the connectors apart. The net effect was that this connector appeared to have a pullout strength of only 2 lb. In reality if the connector were overmolded the latching mechanism would be immobilized, resulting in a pullout strength of up to 56 lb, far in excess of the 10 lb load limit suggested by Exponent to facilitate rapid doffing.

Given the concerns with the length of the 0K, we decided to return our attention to the 0F connector. Using the 0F would allow us to shave as much as another 1 in. of the buckle connector resulting in an overall length of approximately 3.5 in. The only remaining issue with this approach would be finding a way to decrease the latch retention pullout force from 33 lb to 10 lb or less. Discussions with the Lemo sales representative have indicated that this could be accomplished by ordering connectors with custom-made latching pins.

4. PHASE I CONCLUSIONS

The principal conclusions drawn from this Phase I effort to design innovative connector designs were:

Buckle Connector

- The proposed connector concept is composed of a buckle connector where the center guide pin is replaced with a COTS electrical connector. Due to the difficulties of providing a high degree of protection from the ingress of foreign particles and moisture, it is suggested that environmental sealing is best accomplished using a COTS electrical connector with a guaranteed protection index, rather than modifying the buckle connector to serve the same purpose.

- Overmolding the connector's release sleeve will immobilize it and may result in an undesirably high pullout force.

- The latching mechanism on most COTS connectors cannot be removed without compromising the connector's environmental seal. However, the latch retention pullout force can be tailored by altering the latching pins.

- While various connector styles can be successfully incorporated into a buckle connector, environmentally sealed connectors may be undesirable for some applications as they require a relatively bulky buckle design relative to their pin count. As a result, this concept will likely be most suitable for commercial applications where a high degree of environmental protection is not required.

- Due to concerns over bulk, it is felt that it is not currently desirable to integrate an environmentally sealed buckle style connector into the Scorpion Bravo system.

- Non-environmentally sealed buckle connectors can be made quite small and may be desirable for consumer products such as wearable computing platforms.

Other Connector Concepts

- Dovetail connectors, and in fact any connector designs that require a sliding action are extremely difficult to environmentally seal. One advantage of this design, however, is that contaminants are easy to remove from electrical contacts due to the inherent sliding action.

- Electrical connections made with a latching motion similar to that found in cell phone batteries are simple to implement and are relatively easy to environmentally seal.

- Snap connectors are relatively simple to implement and can be used to transmit both power and data. They are not, however, suited to the rigors of outdoor military use as the female side tends to clog up with dirt and mud when not connected.

5. REFERENCES

1. Devine, M., "Physical Fightability Evaluation Methodology," The Natick OFW Open Reviews, October 2-4, 2001.
2. Gemperle, F., Kasabach, C., Stivoric, J., Bauer, M., and Martin, R., "Design for Wearability," The Second International Symposium on Wearable Computers, October 19-20, 1998.

APPENDIX

ARACON® BRAND METAL CLAD FIBER - PRODUCT BULLETIN

Product Bulletin

DU PONT

Aracon®

brand metal clad fiber

Type XS0200G-060 (Conductor Grade)

Aracon® XS0200G-060 represents a new class of electrically conductive silver-clad yarn intended for signal conductor in cables, especially where weight savings is important. Because Aracon® is built on a modified Kevlar® base, the yarns have very high tensile strength per pound, good thermal and dimensional stability, and are solderable and crimpable. These new conductors also show superior performance vs. metal wire products in their flexural endurance life. Aracon® XS0200G-060 is approximately equivalent to AWG 32 in diameter; larger-gauge sizes can be obtained by stranding yarns, as with copper wire conductors. The high strength and textile-like processibility also makes it possible to strand Aracon® with copper conductors to meet a wide range of customer requirements.

Type XS0200G-060 has the following general features:

- Silver-clad for maximum conductivity and solderability.
- Weighs 60% of copper wire at equal volume.
- Construction equivalent to 89 bunched stranded ends of 54 AWG.
- Can be insulated or tape-wrapped on same equipment used for copper conductors.
- Available in 3,000-ft. spools.

Typical Properties

(Not for Purchasing Specifications)

The following data are based on DuPont testing of limited production of this product and therefore may not represent the normal variations seen in continual and repetitive production. However, it is intended that future production runs will use the same processes and machine conditions and that the resulting product will be similar in properties.

Data

Diameter	0.010" (0.254mm)
Approx. AWG	32
Yarn Weight	0.10 lbs./K ft. (0.15kg/km)
Yarn DC Resistance	700 ohms/K ft. (2,295 ohms/km)
Break Load	6.0 lbs.
Est. Operating Temperature Range	–65°C to 200°C

½

Product Bulletin

DU PONT

Aracon®

brand metal clad fiber

Type XN0400E-018 (Shielding Grade)

Aracon® XN0400E-018 represents a new class of conductive yarn intended for braided EMI shielding in cables and harnesses, especially where weight savings is important. The textile-like qualities and flexibility of Aracon® are unique in conductive products, making high coverage easy to obtain without the loss of push-back capability. Since Aracon® is built on a modified Kevlar® base, the yarns have very high strength as well as good thermal and dimensional stability. Exceptional strength and textile-like handling also can permit faster braiding speeds vs. metal wire products.

As with other materials, shielding effectiveness with Aracon® is dependent on details of cable design. The natural tendency for the fine, lightweight fibers to spread out for high coverage (typically >95%) translates into superior shielding effectiveness vs. copper wire, leading to significant weight savings potential. Also, the outstanding strength and processibility of Aracon® uniquely permits it to be braided directly with metal wire products, as well. Such "hybrid" shielding can have tailored electrical performance advantages along with weight savings.

Type XN0400E-018 has the following general features:

- Nickel-clad for maximum thermal stability and salt fog resistance.
- Weighs 40% of copper wire at equal volume.
- Construction equivalent to 178 bunched stranded ends of 54 AWG.
- Can be braided on same equipment used for metal wire.
- Can be soldered or crimped.
- Available in 3,000-ft. spools.

Typical Properties

(Not for Purchasing Specifications)

The following data are based on DuPont testing of limited production of this product and therefore may not represent the normal variations seen in continual and repetitive production. However, it is intended that future production runs will use the same processes and machine conditions and that the resulting product will be similar in properties.

Data	
Braided Bundle Dimensions	
Width	0.022" (0.56mm)
Thickness	0.003" (0.076mm)
Yarn Weight	0.093 lbs./K ft. (0.139kg/km)
Yarn DC Resistance, 20°C	1,300 ohms/K ft. (4,260 ohms/km)
Break Load	10 lbs.
Est. Operating Temperature Range	–65°C to 200°C

For further information, contact:
DuPont
Advanced Fiber Systems
Chestnut Run Plaza
Wilmington, DE 19880-0705
Phone: 800-453-8527
302-999-3358

H-67176 (10/96)

DUPONT

Aracon®

Only by DuPont

Product Bulletin

DUPONT

Aracon®

brand metal clad fiber

Type XS0400E-018 (Shielding Grade)

Aracon® XS0400E-018 represents a new class of conductive yarn intended for braided EMI shielding in cables and harnesses, especially where weight savings is important. The textile-like qualities and flexibility of Aracon® are unique in conductive products, making high coverage easy to obtain without the loss of push-back capability. Since Aracon® is built on a modified Kevlar® base, the yarns have very high strength as well as good thermal and dimensional stability. Exceptional strength and textile-like handling also can permit faster braiding speeds vs. metal wire products.

As with other materials, shielding effectiveness with Aracon® is dependent on details of cable design. The natural tendency for the fine, lightweight fibers to spread out for high coverage (typically >95%) translates into superior shielding effectiveness vs. copper wire, leading to significant weight savings potential. Also, the outstanding strength and processibility of Aracon® uniquely permits it to be braided directly with metal wire products, as well. Such "hybrid" shielding can have tailored electrical performance advantages along with weight savings.

Type XS0400E-018 has the following general features:

- Silver-clad for maximum conductivity and solderability.
- Weighs 40% of copper wire at equal volume.
- Construction equivalent to 178 bunched stranded ends of 54 AWG.
- Can be braided on same equipment used for metal wire.
- Can be soldered or crimped.
- Available in 3,000-ft. spools.

Typical Properties

(Not for Purchasing Specifications)

The following data are based on DuPont testing of limited production of this product and therefore may not represent the normal variations seen in continual and repetitive production. However, it is intended that future production runs will use the same processes and machine conditions and that the resulting product will be similar in properties.

Data	
Braided Bundle Dimensions	
Width	0.022″ (0.56mm)
Thickness	0.003″ (0.076mm)
Yarn Weight	0.093 lbs./K ft. (0.139kg/km)
Yarn DC Resistance, 20°C	1,400 ohms/K ft. (4,590 ohms/km)
Break Load	10 lbs.
Est. Operating Temperature Range	–65°C to 220°C

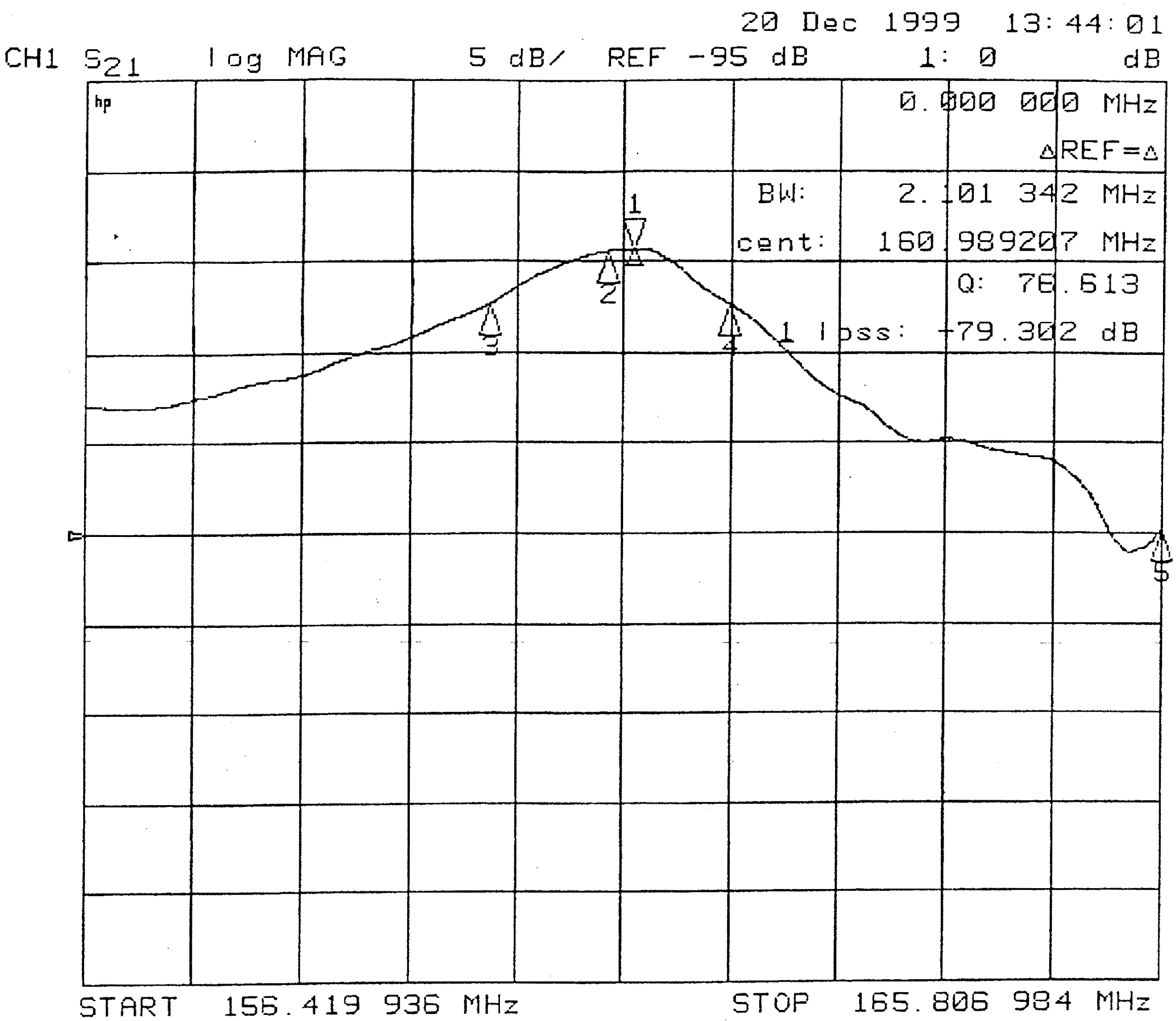
For further information, contact:
DuPont
Advanced Fiber Systems
Chestnut Run Plaza
Wilmington, DE 19880-0705
Phone: 800-453-8527
302-999-3358

H-67177 (10/96)

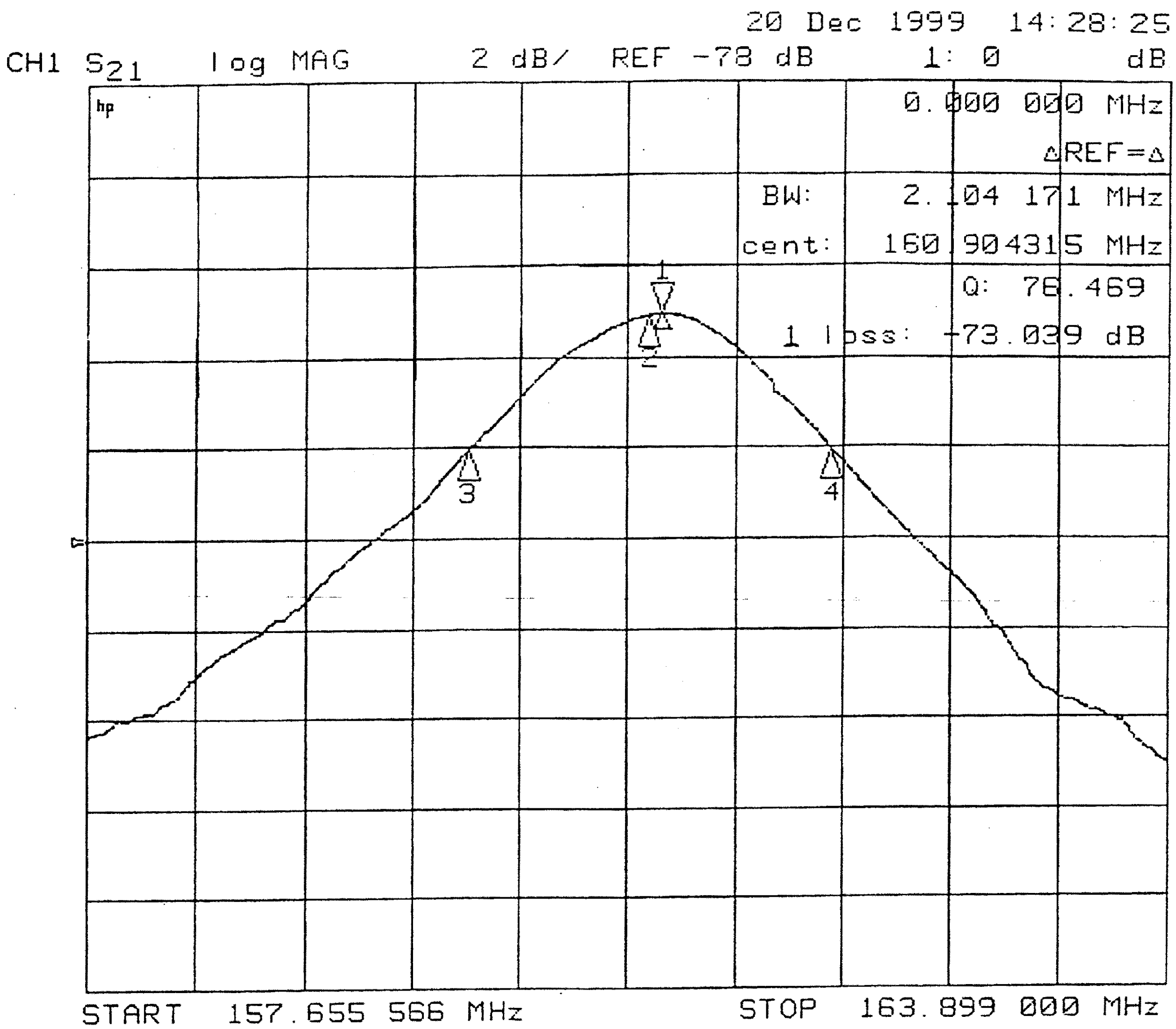
DuPont

Aracon®

Only by DuPont



Number 40 AWG Wire Center Conductor-1st Resonance



Du Pont Arcon Brand Metal clad Fiber Type XS0200G-060 (Yarn Diameter 0.010 in) Center Conductor-1st Resonance

Figure of merit at ~150 MHz (ratio of surface resistance of fiber to surface resistance of Cu)

Fiber	$l_n\left[2\pi\left(\frac{b}{p}\right)\right]$	Perimeter p (in.)	Normalized Surface Resistance R_{SF}/R_{ea}	Measured Quality Factor Q_f
Tinsel	3.82	0.207	4.51	76
XS0200G-060	5.70	0.0314	1.06	76.5
XN0400E-018	4.90	0.070	3.93	37.7
XS0400E-018	4.90	0.070	3.14	47.2
40 AWG-Cu	5.71	0.0311	1.00	76.9